

GASPOL : A Software Package for Design of Gaseous Pollutants Control Equipment

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for the Degree of

Master of Technology

by

Parveen Kumar Goel

to the

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C E R T I F I C A T E

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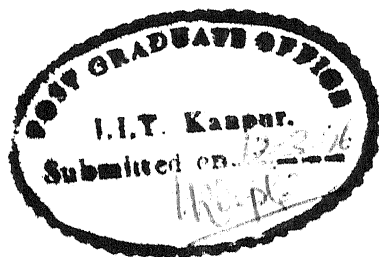
Dr. D. K. Ghosh

Associate Professor

Department of Civil Engineering

I.I.T. Kanpur

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(Parveen Kumar Goe)

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NOMENCLATURE

A	Ratio of the slope of the operating line to the slope of the equilibrium curve, dimensionless
A_a	Active area, ft^2
A_d	Downcomer area, ft^2
Adm	Minimum area through which liquid flows in the downcomer assembly, ft^2
A_h	Hole area, ft^2
A_n	Net area, ft^2
A_r	Total riser area per plate, ft^2
A_s	Total slot area per plate, ft^2
A_t	Column area, ft^2
Bv	Net heating value of vent stream, Btu/scf
C_F	Capacity factor, dimensionless
C_p	Mean heat capacity, $\text{Btu}/\text{ft}^3 \text{ } ^\circ\text{F}$
C_v	Correction of liquid gradient for gas load, dimensionless
C_{vo}	Discharge coefficient, dimensionless
d_c	Cap diameter, in.
d_h	Hole diameter, in.
d_r	Diameter of riser, in.
D	Column diameter, ft.
D_G	Gas diffusivity, ft^2/s or ft^2/hr .
D_L	Liquid diffusivity, ft^2/s or ft^2/hr .
E	Excess air used, dimensionless
E_{mv}	Murphree efficiency, dimensionless
E_{oc}	Overall column efficiency, dimensionless

E_{og}	Point efficiency, dimensionless
f	Friction factor, dimensionless
f_h	Fraction of heat radiated, dimensionless
F	Packing factor, dimensionless
F_W	Weir formula correction factor, dimensionless
g	Acceleration of gravity, 32.2 ft/s^2
g_c	Conversion factor, $\text{lb}_m \cdot \text{ft} / \text{lb}_f \cdot \text{s}^2$
G	Actual gas flow rate, lb/s
G'	Superficial gas mass flow rate, $\text{lb/s} \cdot \text{ft}^2$
G_f	Design gas velocity factor, ft/s
G_s	Flow rate of inert gas, lb/s
h_2	Waste gas heat content, Btu/ft^3
h_3	Auxiliary fuel heat content, Btu/ft^3
h_c	Clear liquid height on tray, in.
h_d	Equivalent headloss through downcomer assembly, in. liquid
h_{ds}	Dynamic seal, in.
h_f	Height of froth on tray, in.
h_h	Headloss due to gas flow through perforations, in. liquid
h_o	Equivalent dry-plate pressure drop through holes, in. liquid
h_{ow}	Height of crest over weir, in.
h_{rc}	Equivalent headloss through wet cap, in. liquid
h_s	Slot height, in.
h_{sk}	Skirt clearance, in.
h_{so}	Slot opening measured from top of slot, in.
h_{sr}	Height of shroud ring, in.
h_{ss}	Static seal distance from top of slot to top of weir, in.

h_w	Weir height, in.
h_σ	Equivalent surface tension headloss, in. liquid
H	Flare stack height, ft.
H_d	Liquid backup in the downcomer, in. liquid
H_{OG}	Height of an overall transfer unit, ft.
ΔH_T	Pressure drop, in. liquid
K	Allowable radiation, Btu/ft ² .hr
K_C	Bubble-cap pressure drop constant, dimensionless
l_w	Weir length, in. or ft.
L	Actual liquid flow rate, lb/s
L'	Superficial liquid mass flow rate, lb/s.ft ²
L_s	Flow rate of pure liquid, lb/s
m	Slope of the equilibrium curve, dimensionless
N_g	Gas-phase transfer unit, dimensionless
N_l	Liquid-phase transfer unit, dimensionless
N_{OG}	Number of overall transfer units
N_P	Number of theoretical plates
p	Pitch, in.
ΔP	Increase in the pressure drop, in. liquid
Q_2	Waste gas flow rate, ft ³ /min
Q_3	Auxiliary fuel flow rate, ft ³ /min
Q_L	Liquid flow rate, gpm
Q'_L	Liquid flow rate, ft ³ /s
Q_V	Gas or vapour flow rate, ft ³ /s
R	Net heat release, Btu/hr.
R_h	Hydraulic radius of the aerated mass, ft.
Re_h	Reynold's modulus, dimensionless

s	Tray spacing, in.
Sc_g	Gas-phase Schmidt number, dimensionless
tp	Plate thickness, in.
U	Maximum design gas velocity, ft/s
U_a	Gas velocity based on active area, ft/s
U_f	Velocity of froth, ft/s
U_h	Gas velocity through holes, ft/s
U_V	Gas velocity based on total area, ft/s
U_{VN}	Gas velocity through the net column cross-sectional area for gas flow, ft/s
V	Actual vapour or gas flow rate, lb/s
W_a	Total flow width across tray normal to flow, ft.
x	Mole fraction of solute in liquid
X	Mole fraction of solute in pure liquid
y	Mole fraction of solute in gas
Y	Mole fraction of solute in inert gas
Z	Height of the column, ft.
Z_L	Distance between weirs, ft.
β	Aeration factor, dimensionless
Δ	Corrected liquid gradient across plate, in. liquid
Δ'	Uncorrected liquid gradient across plate, in. liquid
λ	Stripping factor, dimensionless
μ_G	Gas viscosity, consistent units
μ_L	Liquid viscosity, consistent units
ϕ	Froth density
ψ	Fractional entrainment, dimensionless
ρ_G, ρ_V	Gas density, lb/ft ³

ρ_L Liquid density, lb/ft³
 ρ_W Density of water, lb/ft³
 σ Liquid surface tension, consistent units
 τ Fraction of heat intensity transmitted, dimensionless.

ABSTRACT

In the present work an interactive package for the design of equipment for the removal of gaseous pollutants from the effluent gas stream has been developed. The package has been written in PASCAL. The current version of the package supports the design of absorbers and incinerators for gaseous pollutants control. The different types of absorber, viz., packed column, bubble-cap plate column, and perforated plate column, and the different types of incinerator, viz., thermal incinerator, and open flare incinerator, can be designed using the package. All the input and output data are in the SI units. The outputs of the package are stored in files for subsequent reference. The package has been run for a given set of hypothetical data and the performance of the package has been validated by comparing the results of the package output with those from the literature. Cost analysis has not been included in the present work and the selection of a control equipment for a particular application has been left to the user of the package. The package has been developed to serve as a tool to provide a quick design of various equipment for gaseous pollutants control.

1. INTRODUCTION

1.1 GENERAL

The recent times have been rightly called the "Age of Information Revolution". At present the number of people working in the so-called information age is growing exponentially and its development is faster than could have been envisioned even a few years ago. This era has been characterised by a radical change in the basic philosophy of information acquisition, storage, processing, retrieval and presentation. The change can be attributed to the growth and development of computer technology and its applications, which have given a quantum jump to data processing in terms of increased speeds, reduced costs and better man-machine interaction.

The development of hardware through the years necessitated an equivalent development in software. Thus, software too has advanced from machine language through assembler code to modern computer languages such as FORTRAN, COBOL, PASCAL, C etc. Use of software packages has now been found to save both time and money.

In the field of Environmental Engineering, the number of software packages as well as their applicability is growing rapidly. In the area of air pollution control engineering, the number of software packages available are very few, and there are several areas in which further software development is required. One such area is the design of gaseous pollutants control equipment. Gaseous pollutants are invariably present in almost all the effluent gas streams, and they should be removed prior to

emission. The present work is an effort to develop a software package for design of gaseous pollutants control equipment. This will eliminate the lengthy procedure and going through lengthy calculations for a suitable design to suit a particular situation.

1.2 GASEOUS POLLUTANTS

Primary gaseous air pollutants for which air quality standards have been formulated in many countries include sulphur dioxide, the nitrogen oxides (NO and NO_2), carbon monoxide, and gaseous hydrocarbons. Other pollutants emitted directly to the atmosphere include sulphur trioxide, reduced sulphur compounds such as hydrogen sulphide and carbon disulphide, ammonia, specific hazardous hydrocarbons such as benzene, and a variety of halogenated gases including the chlorofluorocarbons, hydrogen fluoride, hydrogen chloride, and vinyl chloride.

Generally, the formation of these gaseous pollutants can be considered in three categories: combustion sources, industrial manufacturing processes, and natural emission mechanisms. Natural sources of gaseous air pollutants include volcanic gases, ozone from lightning and the ozone layer, gases from forest fires, gases and odours from natural decomposition. Such pollutants constitute background pollution over which control measures can have little, if any, effect. Man-made sources (such as those originating from fuel combustion and industrial processes) cover a wide range of chemical and physical activities and are the major contributors to urban air pollution. In fact, there are very strong arguments for minimising these air pollutant impacts.

Effects of Air Pollutants

The relationship of air contaminants to the ecology, the aggregate of living things as they exist together in nature, is very nearly a total mystery. It is possible to conceive of ecological cycles in which the specific toxicity of a pollutant for a single species could cause an entire food chain to collapse, but the extent to which this might occur is yet unknown.

The toxicological effects of most gaseous pollutants on humans are reasonably well documented. Carbon monoxide has long been known to cause death when exposure to a high concentration (>750 ppm) is encountered (Wark and Warner, 1981). In some cases it has been observed that the effects of exposure to heterogeneous mixtures of gases and particulates at very low concentrations are more severe than the effects of exposure to each pollutant separately. Considerable work continues to be performed on the effects of pollutants on animals, including, for a few species, experiments involving mixed pollutants and mixed gas-aerosol systems (Buonicore and Theodore, 1975).

Injury to vegetation has been one of the earliest manifestations of gaseous air pollutants. Vegetation is more sensitive than animals to many gaseous pollutants. Among the pollutants that can harm plants are sulphur dioxide, hydrogen fluoride, and ethylene. The significant and sometimes devastating effects of sulphur dioxide and fluoride gases were first investigated near the middle of the nineteenth century in Europe, primarily in Germany (Brauer and Varma, 1981).

Gaseous pollutants has long been a significant source of economic loss in urban areas. The damage that gaseous pollutants can do to some materials is well known: ozone in photochemical smog cracks rubber, weakens fabrics, and fades dyes; hydrogen sulfide tarnishes silver; smoke dirties laundry; acid aerosols ruin nylon hose. The damage caused to Taj Mahal by sulfur dioxide is well known.

Considering the harmful effects of gaseous pollutants on man and its environment, the control of these pollutants is a must. This control can be best exercised at the source itself prior to their emission. There are various technologies for the control of gaseous pollutants which will be dealt with in the next chapter.

1.3 OBJECTIVE AND SCOPE OF THE PRESENT WORK

The present work is an effort to develop a software for quick design of gaseous pollutants control equipment so as to provide a tool to the environmental engineers involved in the design of these equipment.

The present study, however, is limited to the following aspects:

1. To provide the basic dimensional parameters of various gaseous pollutants control equipment employing absorption of pollutants to be removed from the effluent gas stream.
2. To provide the basic dimensional parameters of the equipment employing incineration for the control of specific pollutants.
3. To validate the performance of the package by comparing the results of the package output with those from the literature.

2. BACKGROUND INFORMATION

2.1 GENERAL

Gaseous pollutants may be removed from gases either by predominantly physical or chemical processes. In physical processes involving decontamination of waste gases, the pollutants are transferred from the gas phase to either a liquid or a solid phase. Chemical processes are applied to the conversion of pollutants into harmless or at least less harmful substances. The processes commonly used in control technologies for gaseous pollutants include absorption, adsorption, condensation, chemical reaction, incineration, and selective diffusion through a membrane. General advantages and disadvantages of some of these technologies are presented in Table 2.1 through 2.4.

The choice of control technology depends on the pollutant(s) that must be removed, the removal efficiency required, pollutant and gas stream characteristics, and specific characteristics of the site. Experience has led to numerous generalities that should only be considered as such (Air Pollution Engineering Manual, 1992).

1. Absorption removal efficiency is a function of inlet concentration. In general, lower inlet concentrations (below a few hundred ppmv) will result in efficiency levels in the low 90s. Higher inlet concentrations will result in efficiencies in the upper 90s.
2. Absorption becomes a less favoured technology option if a liquid blowdown stream cannot be accommodated at the facility.
3. Carbon adsorption typically can achieve 90+% efficiency at

TABLE 2.1. Advantages and Disadvantages of Absorption Systems
(Packed and Plate Columns)

Advantages

1. Relatively low pressure drop.
2. Standardization in fiberglass reinforced plastic (FRP) construction permits operation in highly corrosive atmospheres.
3. Capable of achieving relatively high mass-transfer efficiencies.
4. Increasing the height and/or type of packing or number of plates can improve mass transfer without purchasing a new piece of equipment.
5. Relatively low capital cost.
6. Relatively small space requirements.
7. Ability to collect particulates as well as gases.

Disadvantages

1. May create water (or liquid) disposal problem.
 2. Product collected wet.
 3. Particulates deposition may cause plugging of the bed or plates.
 4. When FRP construction used, it is sensitive to temperature.
 5. Relatively high maintenance cost.
-

(Source: Air Pollution Engineering Manual, 1992).

TABLE 2.2. Advantages and Disadvantages of Adsorption Systems

Advantages

1. Product recovery may be possible.
2. Excellent control and response to process changes.
3. No chemical disposal problem when pollutant (product) is recovered and returned to process.
4. Capability of systems to provide fully automatic, unattended operation.
5. Capability to remove gaseous or vapour contaminants from process streams to extremely low levels.

Disadvantages

1. Product recovery may require an exotic, expensive distillation or extraction) scheme.
 2. Adsorbent progressively deteriorates in capacity as the number of cycles increases.
 3. Adsorbent regeneration requires a steam or vacuum source.
 4. Relatively high capital cost.
 5. Prefiltering of gas stream may be required to remove any particulate capable of plugging the adsorbent bed.
 6. Cooling of the gas stream may be required to get to the usual range of operation (less than 120°F).
 7. Relatively high steam requirements to desorb high-molecular-weight hydrocarbons.
-

(Source: Air Pollution Engineering Manual, 1992).

TABLE 2.3. Advantages and Disadvantages of Combustion Systems

Advantages

1. Simplicity of operation.
2. Capability to provide steam generation or heat recovery in other forms.
3. Capability for high destruction efficiency of organic contaminants.

Disadvantages

1. Relatively high operating costs (particularly associated with fuel requirements).
 2. Potential for flashback and subsequent explosion hazard.
 3. Catalyst poisoning (in the case of catalytic incineration).
 4. Incomplete combustion can create potentially worse pollution problems.
-

(Source: Air Pollution Engineering Manual, 1992).

TABLE 2.4. Advantages and Disadvantages of Condensers

Advantages

1. Pure product recovery (in the case of indirect-contact condensers).
2. Water used as the coolant in an indirect contact condenser (i.e., shell-and-tube heat exchanger) does not contact the contaminated gas stream and can be reused after cooling.

Disadvantages

1. Relatively low removal efficiency for gaseous contaminants (at concentrations typical of pollution control applications).
 2. Coolant requirements may be extremely expensive.
-

(Source: Air Pollution Engineering Manual, 1992).

gaseous pollutant concentrations greater than a few hundred ppmv. At higher concentrations (greater than 1000 ppmv), efficiencies can exceed 95%.

4. Adsorption becomes a less favoured technology option if the mixture of recovered organics cannot be returned to the process with minimum additional treatment. In such cases, it may be more cost-effective to incinerate the recovered organics that have been significantly concentrated by the adsorption process.
5. At low gaseous pollutant concentrations (less than 100 ppmv), incineration can generally achieve 90-95% efficiency with thermal incineration slightly better than catalytic at the lowest concentrations.
6. At higher gaseous pollutant concentrations (greater than 100 ppmv), incineration typically can achieve 95-99% efficiency.
7. Incineration can produce products of incomplete combustion or otherwise undesirable by-products that may require additional controls.
8. Condensation generally needs relatively high inlet concentrations (greater than a few thousand ppmv) to achieve efficiencies in the 80+% range.
9. Condensation generally cannot meet high efficiency requirements without the use of very low temperatures (e.g., use of liquid nitrogen) or high pressure.
10. Typically, only incineration and absorption technologies are able to achieve greater than 99% gaseous pollutant removal efficiency on a consistent basis.

2.2 ABSORPTION

The removal of one or more gaseous components from a gas mixture by absorption is probably the most important operation in the control of gaseous pollutant emissions. The transfer of contaminant by absorption conventionally refers to the intimate contacting of a mixture of the gas and liquid (conventional wet scrubbing) and their subsequent separation into cleaned gas and contaminated liquid streams. Capacity is generally determined by the flow rate at which the scrubber will become inoperable because of excessive or complete carryover of liquid by gas, or at which pressure drop will become excessive. The driving force for absorption is the difference between partial pressure of the soluble gas in the gas mixture and its vapour pressure just above the surface of the liquid.

In most processes involving the absorption of a gaseous pollutant from an effluent gas stream, the gas stream's inlet conditions (flow rate, composition, and temperature) are usually known. The temperature and composition of the inlet liquid and the composition of the outlet gas are usually specified. The main objectives, then, in the design of an absorption column are the determination of the solvent flow rate and the calculation of the principal dimensions of the equipment. These objectives can be attained by evaluating, for a selected solvent at a given flow rate, the number of theoretical separation units (stages or plates) and converting them into practical units of column height or number of actual plates by means of existing correlations.

The general design procedure consists of a number of steps that have to be taken into consideration. These include the following:

1. Selection of solvent.
2. Selection of gas-liquid equilibrium or solubility data.
3. Calculation of liquid-gas ratio.
4. Selection of column.
5. Calculation of column diameter (for packed columns, this is usually based on flooding conditions, and for plate columns, on the optimum gas velocity or the liquid-handling capacity of the plate).
6. Estimation of column height or the number of plates.
7. Determination of pressure drop through the column.

2.2.1 Mass Balance

In order to determine some of the operating characteristics of an absorption tower, it is necessary to make mass balances on the transfer process and to construct an operating line on the equilibrium diagram. It is recommended that engineers work with the concentration in terms of moles of solute per mole of pure solvent or moles of solute per mole of inert gas. This makes the mass balance calculations much easier (Chermisinoff, 1977).

Let

- x = mole fraction of solute in liquid
- y = mole fraction of solute in gas
- X = mole fraction of solute in pure liquid
- Y = mole fraction of solute in inert gas
- L_s = flow rate of pure liquid

G_s = flow rate of inert gas.

It is easily shown that

$$X = \frac{x}{1 - x} \quad (2.1)$$

and

$$Y = \frac{y}{1 - y} \quad (2.2)$$

The basic arrangement of a counter flow packed tower is shown in Figure 2.1. Dirty gas enters the bottom and the cleaned gas exits at the top of the tower. Clean liquid enters the top of the tower while contaminated liquid is withdrawn from the bottom. Taking the mass balance across the scrubber, we have

$$G_s Y_{in} + L_s X_{in} = G_s Y_{out} + L_s X_{out} \quad (2.3)$$

$$G_s (Y_{in} - Y_{out}) = L_s (X_{out} - X_{in}) \quad (2.4)$$

$$Y_{in} - Y_{out} = \frac{L_s}{G_s} (X_{out} - X_{in}) \quad (2.5)$$

When the line represented by Eq. (2.5) is drawn on an equilibrium diagram, it is called an operating line (Figure 2.2). When transfer of solute is from gas to liquid, the operating line is above the equilibrium line and the operation is called absorption. On the other hand, when transfer is from liquid to gas, the operating line is below the equilibrium line and the operation is known as stripping. For cocurrent flow, the position of the operating line is quite different from that for counter current flow (Treybal, 1968), and is not addressed in the present work.

The equilibrium curve will shift in position as the operating temperature, operating pressure, and solvent composition are altered. There is usual practice to add certain chemicals to the

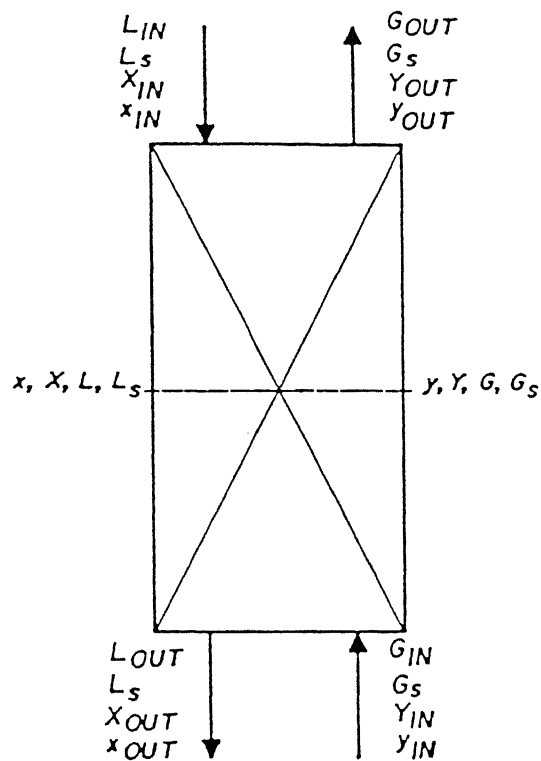


Figure 2.1 Flow Schematic Across Absorption Column

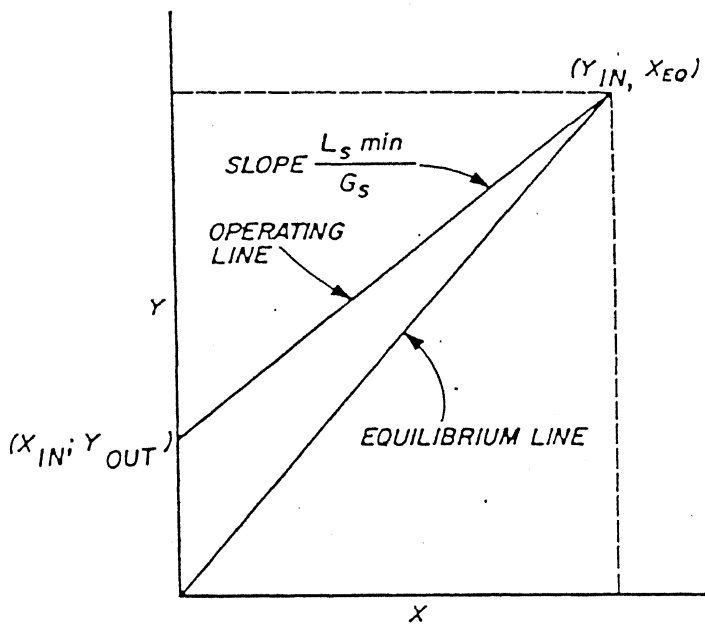


Figure 2.2 Relative Positions of the Operating and Equilibrium Line on X-Y Diagram for a Counterflow Absorption Column

solvent so that the driving force (vertical intercept between the operating line and the equilibrium curve) is increased. Since the equilibrium curve data has to be entered into the package by the user, this situation (absorption aided by chemicals) can be taken care of.

2.2.2 Liquid Requirement

Construction of an operating line as discussed is required to determine the liquid requirement in absorption. While designing the absorber, concentration of solute both in gas to be treated and solvent to be used are known. Furthermore, minimum acceptable concentrations of objectionable materials in the gas and gas flow rates are also known. For minimum liquid rate, concentrations Y_{in} and X_{out} will be at equilibrium. Hence, that condition is represented by a point on the equilibrium curve (Y_{in} , X_{eq}). The slope of the operating line between (Y_{in} , X_{eq}) and (Y_{out} , X_{in}) represents the condition at minimum liquid flow rate. The slope is $(L_s/G_s)_{min}$. Correspondingly, the value of L_s is the minimum solvent rate for the given gas stream conditions.

The minimum solvent rate is highly undesirable. At the point of contact between the operating and equilibrium lines the driving force for mass transfer is zero. Hence it would take an infinitely tall absorber to accomplish the desired separation. Therefore, the design rate must be larger than the minimum. If the rate is just slightly greater than the minimum, the average driving force still will be quite small, and the tower might be inordinately tall. On the other hand, a large average driving force is attained at the expense of a much larger liquid solvent rate. This means large

pumping losses. However, in this latter case the height of the tower can be relatively small. The ultimate choice lies between these extremes, and must be tempered by economics and other considerations. As a general operating principle, an absorber is typically designed to operate at liquid rates which are 30 to 70 percent greater than the minimum rate (Wark and Warner, 1981). In case more than one component is present in the gas stream, the liquid requirement for each of the component is determined and the largest value is chosen.

2.2.3 Description of Equipment

The principal types of gas absorption equipment may be classified as follows:

1. Packed columns (continuous operating)
2. Plate columns (stage operating)
3. Miscellaneous.

Of the three categories, the packed column is by far the most commonly used for the absorption of gaseous pollutants. Only packed column and plate column have been incorporated in the present study, and are discussed in details in the subsequent sections. Relative advantages of packed and plate column are as follows:

Packed column:

1. Lower pressure drop.
2. Simpler and cheaper to construct.
3. Preferable for liquids with high foaming tendencies.

Plate column:

1. Less susceptible to plugging.

2. Less weight.
3. Less of a problem with channeling.
4. Temperature surge will result in less damage.

Venturi scrubber is another type of absorber which finds some application in the control of gaseous pollutants. In this device the gas is absorbed in the throat of a venturi by a stream of absorbing liquid sprayed into the convergent duct and/or throat section. It is also used for removing fine particulate matter from effluent gas stream. Design of venturi scrubber for particulate removal, using a computer, has been done by Sinha (1995) and the same can be modified for the simultaneous removal of gaseous and particulate pollutants. Venturi scrubber, however, is not incorporated in the present work.

2.3 ABSORPTION: PACKED COLUMN

Packed columns, used for the continuous contact of liquid and gas, are usually vertical columns that have been filled with packing or devices for providing large liquid surface area. The liquid is distributed over and trickles down through the packed bed, thus exposing a large surface area to contact the gas. The counter current packed column (Figure 2.3) is the most common type of equipment encountered in gaseous pollutant control for the removal of the undesirable gas, vapour, or odour.

The gas stream (containing the pollutant) moves upward through the packed bed against an absorbing or reacting liquor (solvent-scrubbing solution), which is injected at the top of the packing. This results in the highest possible efficiency. Since the solute concentration in the gas stream decreases as it rises through the

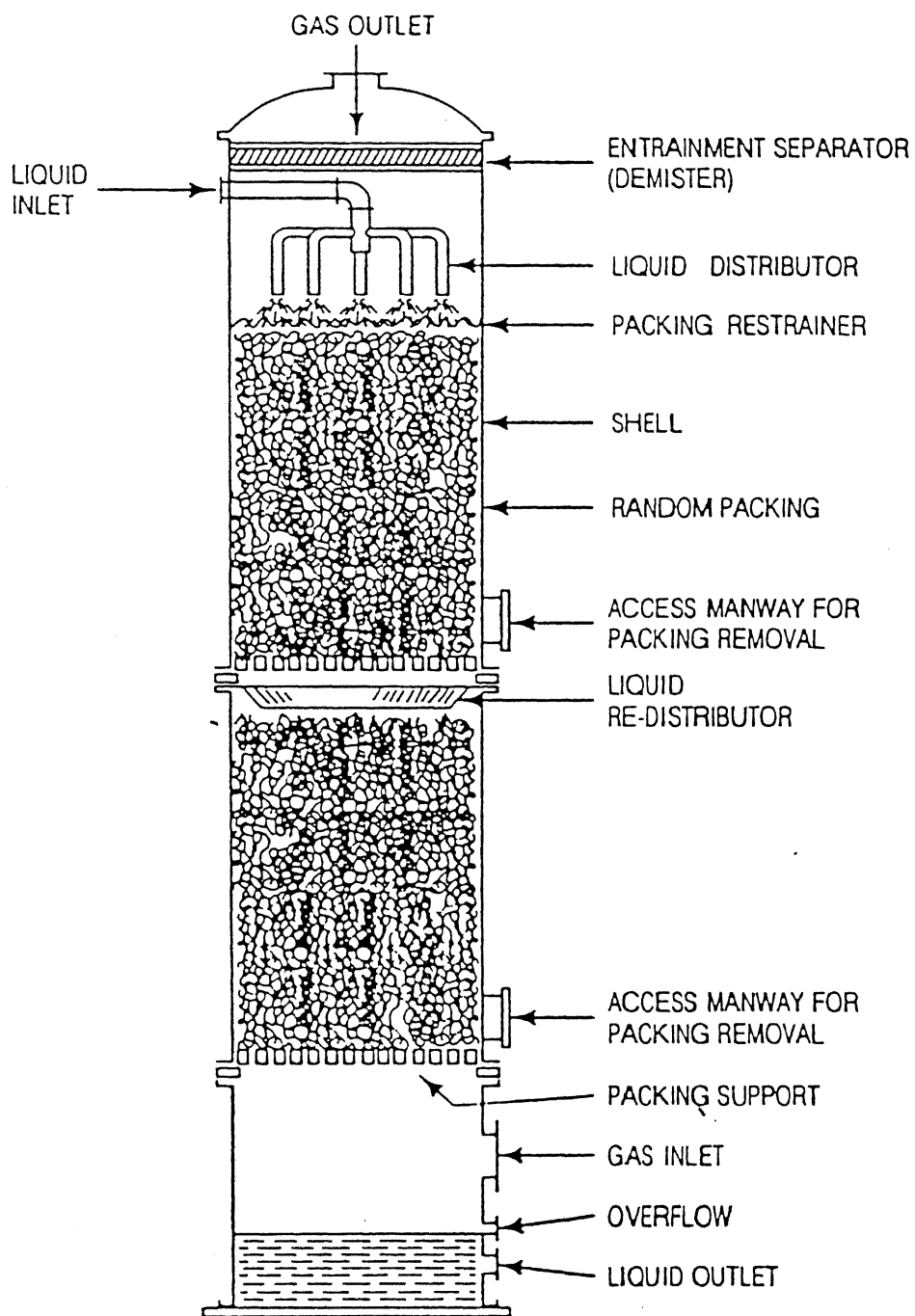


Figure 2.3 Typical Countercurrent Packed Column

column, there is constantly fresher solvent available for contact. This provides the maximum average driving force for the diffusion process throughout the packed bed.

Occasionally, cocurrent flow may be used, where the gas stream and solvent both enter the top of the column. In general, cocurrent flow is not used too often except in the case of a very tall column built in two sections, both located on the ground, with the second section operating in cocurrent flow merely as an economy measure to save on the large diameter gas pipe connecting the two (Air Pollution Engineering Manual, 1992). Packed columns may also operate in cross flow where the gas stream moves horizontally through the packed bed and is irrigated by the scrubbing liquid, which flows vertically down through the packing. The present work incorporates the design of counter current packed columns only.

2.3.1 Packings

The packing is the heart of the performance of this type of equipment. Its proper selection entails an understanding of packing operational characteristics and the effect of performance of the points of significant physical difference among the various types. The main points to be considered in choosing the column packing include:

1. Durability and corrosion resistance. (The packing should be chemically inert to the fluids being processed.)
2. Free space per cubic foot of packed space. (This controls the liquor holdup in the column, as well as the pressure drop across it. Ordinarily, the fractional void volume, or fraction of free space, in the packed bed should be large.)

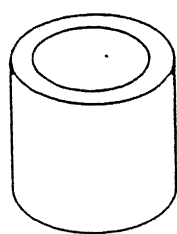
3. Wetted surface area per unit volume of packed space. (This is very importance since it determines the interfacial surface between liquid and gas. It is rarely equal to the actual geometric surface since the packing is usually not completely wetted by the fluid.)
4. Frictional resistance to the flow of gas. (This affects the pressure drop over the column.)
5. Packing stability and structural strength to permit easy handling and installation.
6. Weight per cubic foot of packed space.
7. Cost per square foot of effective surface:

Figure 2.4 illustrates the shapes of some of the conventional packings.

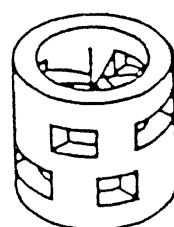
2.3.2 General Packed Column Design

Once all the streams entering and leaving the column and their constituents are identified, flow rates calculated, and operating conditions determined, the physical dimensions of the column can be calculated. The column must be of sufficient diameter to accommodate the gas and liquid and of sufficient height to ensure that the required amount of mass is transferred with the existing driving force.

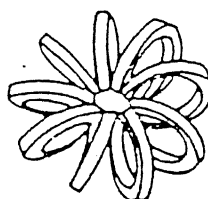
In a packed column that is operating at a given liquid rate and the gas rate is gradually increased, the drag on the liquid increases gradually. This, of course, both increases the pressure drop and prevents the packing from mixing the gas and liquid effectively, and ultimately some liquid is even carried back up the column. This undesirable condition, known as flooding, occurs



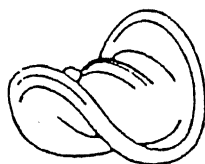
Raschig ring



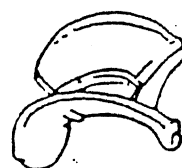
Pall ring



Tellerette



Berl saddle



Intalox saddle

Figure 2.4 Shapes of Conventional Packings

fairly abruptly, and the superficial gas velocity at which it occurs is called the flooding velocity. The calculation of column diameter is based on flooding considerations, the usual operating range being taken as 50-75% of the flooding rate (Air Pollution Engineering Manual, 1992).

The relationship between increase in the pressure drop per unit height, $\Delta P/Z$ and other important tower variables — liquid and gas rates, liquid and gas stream densities and viscosities, and type or packing — has been extensively studied on an experimental basis. A widely accepted correlation among these parameters is shown in Figure 2.5. In the correlation, if G' and L' are expressed in $\text{lb}/\text{s}\cdot\text{ft}^2$, then g_c has a value of $32.2 \text{ lb}_m\cdot\text{ft}/\text{lb}_f\cdot\text{s}^2$. In addition μ_L must be in centipoises, and ρ_G , ρ_L , and ρ_W in lb_m/ft^3 . One new quantity in the correlation is G' , the superficial gas mass flow rate. This is defined as the actual gas flow rate divided by the empty cross-sectional area of the column. A similar definition holds for a superficial liquid mass flow rate, L' . The other new quantity in the correlation is the packing factor, F . Table 2.5 lists values of F for different sizes of various packings. The top line in the Figure 2.5 represents the flooding condition. This single correlation allows us to estimate two important tower parameters: the required column diameter and the expected pressure drop per unit height of the column. The general procedure consists of evaluating the abscissa value $(L'/G')(\rho_G/\rho_L)^{0.5}$ first, and then determining the corresponding value of ordinate for flooding condition from Figure 2.5. Knowing the value of the ordinate, the other parameters being known, we can

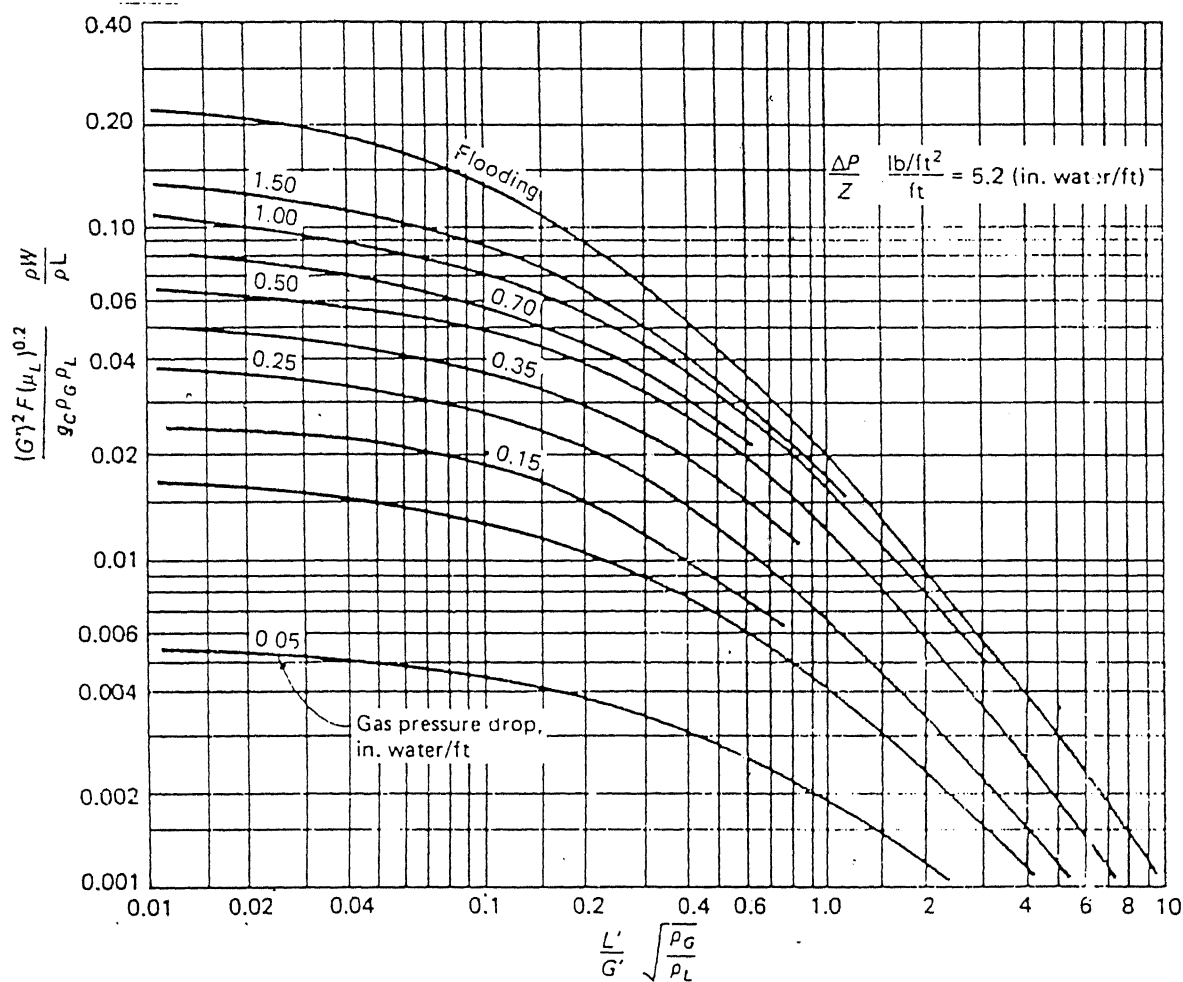


Figure 2.5 Flooding and Pressure Drop in Random Packed Columns
(Source : Wark and Warner, 1981)

TABLE 2.5. The Packing Factor, F, for Random Packing.

		Nominal packing size (inches)									
Packing type	Material	1/4	3/8	1/2	5/8	3/4	1	1 $\frac{1}{4}$	1 $\frac{1}{2}$	2	
Raschig rings	Ceramic	1600	1000	640	380	255	160	95	65	65	
Raschig rings	1/32" metal	700	390	300	170	185	115				
Raschig rings	1/16" metal			410	290	230	137	110	83	57	
Berl saddles	Ceramic	900		240		170	110		65	45	
Pall rings	Plastic				97		52		40	25	
Pall rings	Metal				70		48		28	20	
Intalox saddles	Ceramic	725	330	200		145	98		52	40	

(Source: Air Pollution Engineering Manual, 1992).

solve for G' , the superficial gas mass flow rate. This, of course, is the value of G' associated with flooding. For proper columns design we use 50 to 75% of this flood point value. The actual gas flow rate, G divided by the superficial gas flow rate, G' gives the cross-sectional area of the column. As a word of caution, it may be necessary to determine the area of the column at both the top and the bottom of the column, since they will differ. For a margin of safety the larger value of the area is chosen for design purposes. The other important column parameter is the height of the column which is given by

$$Z = N_{OG} H_{OG} \quad (2.6)$$

where

N_{OG} = number of overall transfer units

H_{OG} = height of an overall transfer unit, feet

Z = height of the column, feet.

2.3.3 Evaluation of the Number of Transfer Units

In most air pollution applications, the pollutant to be absorbed is in the very dilute range. If the equilibrium and operating lines are both straight within the operating range (Henry's law applies), and the number of transfer units is given by (Air Pollution Engineering Manual, 1992):

$$N_{OG} = \frac{\ln \left[\frac{(Y_1 - mX_2)}{(Y_2 - mX_2)} \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right]}{1 - \left(\frac{1}{A} \right)} \quad (2.7)$$

where

$$A = L/mG$$

m = slope of the equilibrium curve.

The subscripts 1 and 2 indicates the conditions at the bottom and the top of the column respectively.

2.3.4 Evaluation of the Height of a Transfer Unit

Qualitatively, the height of a transfer unit is a measure of the height of a contactor required to effect a standard separation, and it is a function of the gas flow rate, the liquid flow rate, the type of packing, and the chemistry of the system. The overall height of a transfer unit can be evaluated by

$$H_{OG} = H_G + \left(\frac{mG}{L} \right) H_L \quad (2.8)$$

where

H_{OG} = Height of a transfer unit, ft

H_G = Gas-phase height of a transfer unit, ft

H_L = Liquid-phase height of a transfer unit, ft

G = Actual gas flow rate, lb/s

L = Actual liquid flow rate, lb/s

m = Slope of the equilibrium curve.

The gas-phase and liquid-phase transfer heights have been correlated over a wide range of experimental data. Generalized equations for H_G and H_L are given below (Wark and Warner, 1981):

$$H_G = \frac{\alpha (G')^\beta}{(L')^\gamma} \left(\frac{\mu_G}{\rho_G D_G} \right)^{0.5} \quad (2.9)$$

and

$$H_L = \phi \left(\frac{L'}{\mu_L} \right)^\eta \left(\frac{\mu_L}{\rho_L D_L} \right)^{0.5} \quad (2.10)$$

where

G' = Superficial gas flow rate, lb/hr.ft²

L' = Superficial liquid flow rate, lb/hr.ft²

ρ_G = Density of the gas, lb/ft³

ρ_L = Density of the liquid, lb/ft³

μ_G = Viscosity of the gas, lb/hr.ft

μ_L = Viscosity of the liquid, lb/hr.ft

D_G = Gas diffusivity, ft²/hr

D_L = Liquid diffusivity, ft²/hr

α, β, γ = Packing constants for use in determining gas-phase height (as given in Table 2.6)

ϕ, η = Packing constants for use in determining liquid-phase height (as given in Table 2.7).

2.4 ABSORPTION: PLATE COLUMN

Plate columns are essentially vertical cylinders in which the liquid and gas are contacted in stepwise fashion (staged operation) on plates or trays, in a manner shown schematically for one type

TABLE 2.6. Constants for Use in Determining Gas-Phase Height of a Transfer unit

Packing	α	β	γ	Superficial gas-flow rate (lb/hr.ft ²)	Superficial liquid-flow rate (lb/hr.ft ²)
Raschig rings					
3/8 in	2.32	0.45	0.47	200 - 500	500 - 1500
1 in	7.00	0.39	0.58	200 - 800	400 - 500
	6.41	0.32	0.51	200 - 600	500 - 4500
1 1/2 in	17.30	0.38	0.66	200 - 700	500 - 1500
	2.58	0.38	0.40	200 - 700	1500 - 4500
2 in	3.82	0.41	0.45	200 - 800	500 - 4500
Berl saddles					
1/2 in	32.40	0.30	0.74	200 - 700	500 - 1500
	0.811	0.30	0.24	200 - 700	1500 - 4500
1 in	1.97	0.36	0.40	200 - 800	400 - 4500
1 1/2 in	5.05	0.32	0.45	200 - 1000	400 - 4500

(Source: Buonicore and Theodore, 1975).

TABLE 2.7. Constants for Use in Determining Liquid-Phase Height of a Transfer Unit

Packing	ϕ	η	Superficial liquid-flow rate (lb/hr.ft ²)
Raschig rings			
3/8 in	0.00182	0.46	400 - 15,000
1/2 in	0.00357	0.35	400 - 15,000
1 in	0.0100	0.22	400 - 15,000
1 $\frac{1}{2}$ in	0.0111	0.22	400 - 15,000
2 in	0.0125	0.22	400 - 15,000
Berl saddles			
1/2 in	0.00666	0.28	400 - 15,000
1 in	0.00588	0.28	400 - 15,000
1 $\frac{1}{2}$ in	0.00625	0.28	400 - 15,000

(Source: Buonicore and Theodore, 1975)

in Figure 2.6. The liquid enters at the top and flows downward via gravity. On the way, it flows across each plate and through a downspout to the plate below. The gas passes upward through openings of one sort or another in the plate, then bubbles through the liquid to form a froth, disengages from the froth, and passes on to the next plate above. The overall effect is a multiple countercurrent contact of gas and liquid. Each plate of the column is a stage since on the plate on which the fluids are brought into intimate contact, interphase diffusion occurs and the fluids are separated.

The tray type columns can be of three types, namely

1. Bubble cap trays
2. Sieve trays
3. Valve trays.

Bubble cap trays are inverted bell shaped caps with slots placed over specifically prepared risers. Bubble caps are the most versatile type of tray available. They can operate even at very high or very low flow rates. They can tolerate large changes in input/output flow rates without significant change in efficiency. Their only drawback is their high cost of fabrication.

Sieve trays are the most commonly used trays. They have the greatest advantage of extremely low cost of fabrication. In simple terms sieve tray is a plate with holes punched in it. Due to its simplicity in fabrication, the cost of sieve tray is low. They are not as versatile as the bubble cap trays are in operation. At low flow rates weeping can be high. This reduces the tray efficiency and the desired separation is not achieved. At high flow rates

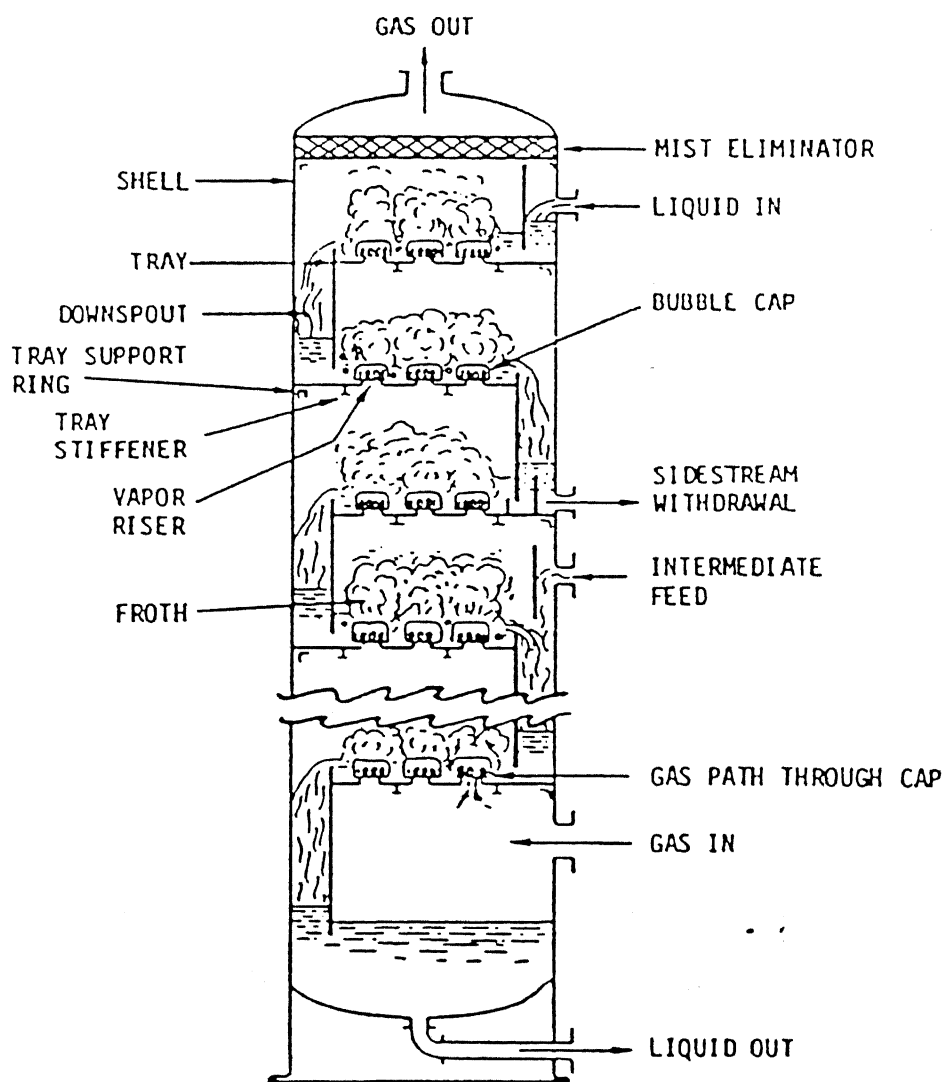


Figure 2.6 Typical Bubble-cap Plate Column

there are more chances of large amounts of liquid being entrained in the vapour. This also reduces the efficiency of separation. Therefore, they have high efficiencies only in a narrow range of input/output flow rates.

Valve trays constitute the third type of tray tower available. Valve trays consists of perforations covered with liftable lids or valves which rise and fall with variation in vapour flow rates. The lid thus acts as a check to limit liquid weeping and dumping at low vapour flow rates. Accordingly, the chief advantage of valve trays is that high efficiency can be maintained over a wide range of operating throughputs. Since they are more complex mechanically, their fabrication is somewhat more expensive than that of sieve trays. However, valve trays are not incorporated in the present study.

2.4.1 General Plate Column Design

The most important design considerations for plate columns include calculation of the column diameter, type and number of plates to be used (for example, bubble cap or sieve plates), actual plate layout and physical design, and plate spacing (which, in turn, determines the column height).

Column diameter

The column diameter, and consequently its cross-section, must be sufficiently large to handle the gas and liquid at velocities that will not cause flooding or excessive entrainment. The superficial gas velocity for a given type of plate at flooding is given by the relation

$$U_{VN} = C_F [(\rho_L - \rho_V) / \rho_V]^{0.5} \quad (2.11)$$

where

U_{VN} = gas velocity through the net column cross-sectional area for gas flow, ft/s

ρ_L, ρ_V = liquid and vapour densities, respectively, lb/ft³

C_F = an empirical coefficient that depends on the type of plate and operating conditions (known as capacity factor).

The net cross-section is the difference between the column cross-section and the area taken up by downcomers. In actual design, some percent of U_{VN} is usually used: for non-foaming liquids 80 to 85% of U_{VN} , and 75% or less for foaming liquids (Air Pollution Engineering Manual, 1992). Thus, knowing the value of gas velocity, U_{VN} , the net cross-sectional area of the column can be determined. The value of U_{VN} can be determined from Figure 2.7 which correlates the flooding capacity of the tray through plate spacing and flow parameter $(L/V)(\rho_V/\rho_L)^{0.5}$ to the capacity parameter $U_{VN}[\rho_V/(\rho_L - \rho_V)]^{0.5}$.

Figure 2.7 may be used for both bubble-cap plates and perforated plates to determine the flooding gas velocity for a given value of flow parameter and plate spacing within about 10%, with the following restrictions:

1. The system is a low-foaming or non-foaming type.
2. The weir height is less than 15% of the tray spacing.
3. The ratio of slot area, or hole area, to active plate area is equal to or greater than 0.1. For hole-to-active area ratios of less than 0.1, it is recommended that the flooding capacity be modified by the following factors

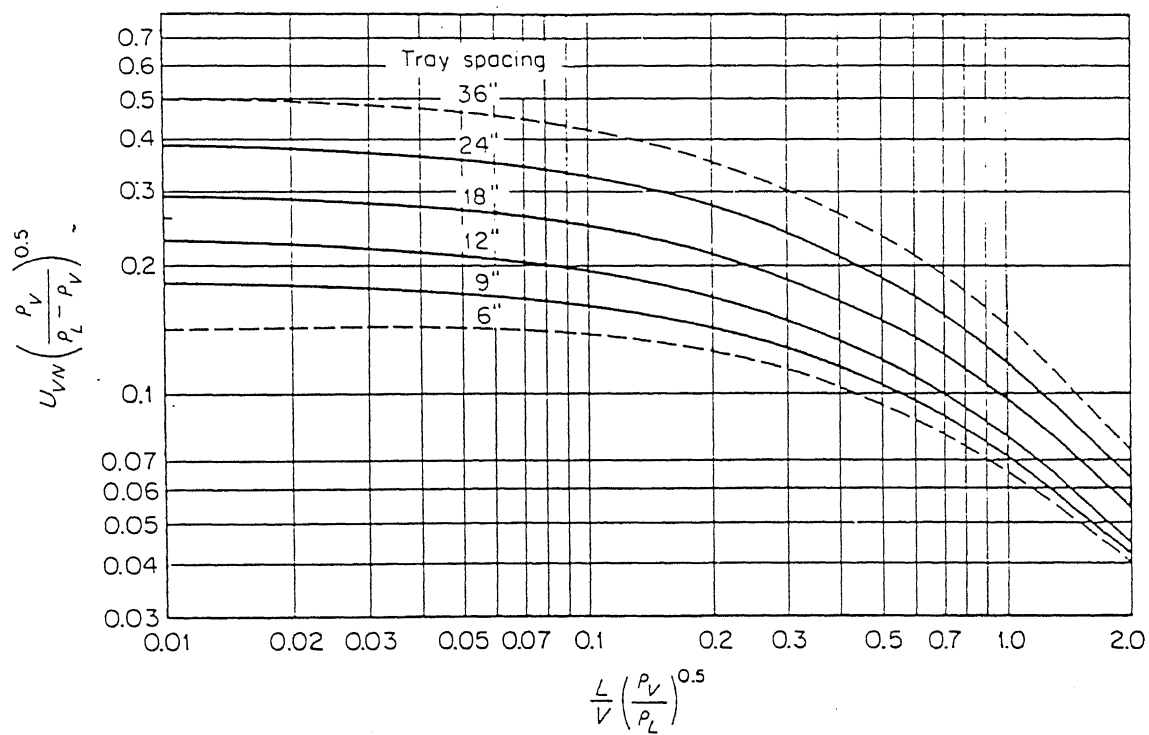


figure 2.7 Flooding Limits for Bubble-cap and Perforated Plates
(Source : Winkle, 1967)

A_h/A_a	Multiply U_{VN} by
0.10	1.00
0.08	0.90
0.06	0.80

4. The plate spacing of 6 and 9 in. do not apply to bubble-cap plates.
5. The system surface tension is 20 dynes/cm. For surface tensions different from 20 dynes/cm, the flooding gas velocity from Figure 2.7 is multiplied by $(\sigma/20)^{0.2}$.

Number of plates

For cases in which both the operating line and the equilibrium curve may be considered straight (dilute solutions), the number of theoretical plates may be determined directly without recourse to graphical techniques. This will frequently be the case for relatively dilute gas (as usually encountered in air pollution control) and liquid solutions where, more often than not, Henry's law is applicable. For such cases, the Kremser-Brown-Souders equation applies for determining the number of theoretical plates, N_p (Buonicore and Theodore, 1975)

$$N_p = \frac{\log \left[\left(\frac{Y_1 - mX_2}{Y_{N_p+1} - mX_2} \right) \left(1 - \frac{1}{A} \right) + \frac{1}{A} \right]}{\log A} \quad (2.12)$$

where

$$A = L/mG$$

$$m = \text{Slope of the equilibrium curve.}$$

The solute concentrations in the gas stream, Y_1 and Y_{N_p+1} represent inlet and outlet conditions. The number of actual plates are,

then, equal to the number of theoretical plates divided by the overall efficiency of the plate which is explained in the subsequent subsection.

Column height

The column height is determined from the product of the number of actual plates and the plate spacing chosen. Tray spacing has an important effect on flooding and entrainment. Tray spacing from 6 to 54 inches have been used in commercial columns (Smith, 1963). Actually, it is usually mechanical factors which decide tray spacing. For example, it is necessary to provide sufficient space between trays so as to facilitate inspection and repairs.

General tray types

General tray types are classified by the mode of liquid flow on the tray. The more common and recommended tray types are illustrated in Figure 2.8. The crossflow tray, wherein the liquid flows directly across the tray, is the most common tray type. This represents the simplest tray construction and is consequently the most economical to fabricate. A guide for tentative selection of tray type is given in Table 2.8. The ranges given in Table 2.8 are approximate and are intended for tentative selection only. The final selection of tray type should be based upon the results of complete tray dynamic calculations for the specific application.

Tray design

The object of good tray design is to determine the optimum design, which means selection of the optimum combination of design elements which will give least total cost. The total cost depends on the operating cost and the installation cost of the column. In

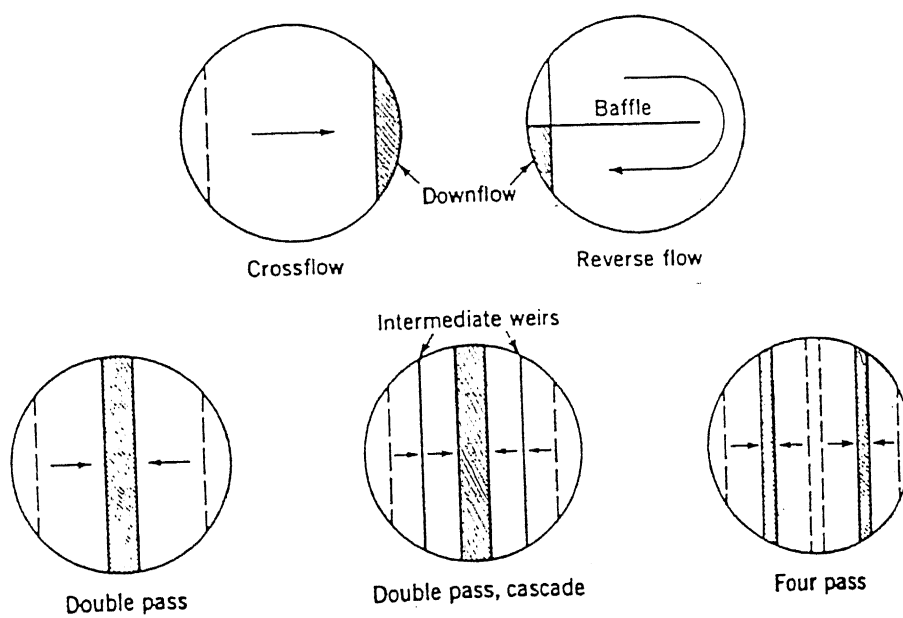


Figure 2.8 Recommended General Tray Types

TABLE 2.8 Guide for Tentative Selection of Tray Type

Estimated tower dia, ft	Range of liquid capacity, gpm			
	Reverse flow	Cross flow	Double pass	Cascade double pass
3	0 - 30	30 - 200		
4	0 - 40	40 - 300		
6	0 - 50	50 - 400	400 - 700	
8	0 - 50	50 - 500	500 - 800	
10	0 - 50	50 - 500	500 - 900	900 - 1400
12	0 - 50	50 - 500	500 - 1000	1000 - 1600
15	0 - 50	50 - 500	500 - 1100	1100 - 1800
20	0 - 50	50 - 500	500 - 1100	1100 - 2000

(Source: Smith, 1963).

the present work, while evaluating the tray parameters, a multi-dimensional search is carried out to minimize the pressure drop. The pressure drop directly relates to the boiler temperature and the pumping cost. So in effect the pressure drop is directly related to the operating cost of the column. Thus, an effort is being made in the present work to minimize the operating cost of the column. The installation cost of the column, however being site specific, is not addressed in the present work.

2.4.2 Tray Hydraulics: Bubble Cap Trays

Liquid entrainment

As the vapour rises from the tray it carries some liquid droplets along with. These droplets get carried over by the vapour to the tray above. This reduces the efficiency of separation. So liquid entrainment should be minimum. Entrainment can be predicted

from Figure 2.9. If the entrainment is less than 0.10 then the tray performance is good else the tray spacing has to be increased.

Design standards

Area terms. The area on a bubble-cap tray can be classified into four categories as shown in Figure 2.10. The allocated cap area is that area allocated to the bubble caps, sometimes referred to as the active tray area. The distribution of area according to these four classifications varies with the tower diameter, type of tray, and other factors. However, on the basis of experience certain practical ranges have been determined, and these are summarized in Table 2.9. For well designed trays, the allocated cap area is usually between 60 and 70 percent of the column area.

TABLE 2.9 Typical Distribution of Areas as Percent of Tower Area
(Allocated cap area is determined by difference)

Tower dia, ft	Downflow area		Liquid-distribution area			End wastage
	Cross- flow	Double pass	Cross flow	Double pass	Cascade double	
3	10 - 20		10 - 25			10 - 30
4	10 - 20		8 - 20			7 - 22
6	10 - 20	20 - 30	5 - 12	15 - 20		5 - 18
8	10 - 20	18 - 27	4 - 10	12 - 16		4 - 15
10	10 - 20	16 - 24	3 - 8	9 - 13	20 - 30	3 - 12
12	10 - 20	14 - 21	3 - 6	8 - 11	15 - 25	3 - 10
15	10 - 20	12 - 18	2 - 5	6 - 9	12 - 20	2 - 8
20		10 - 15		5 - 7	9 - 15	2 - 6

(Source: Smith, 1963).

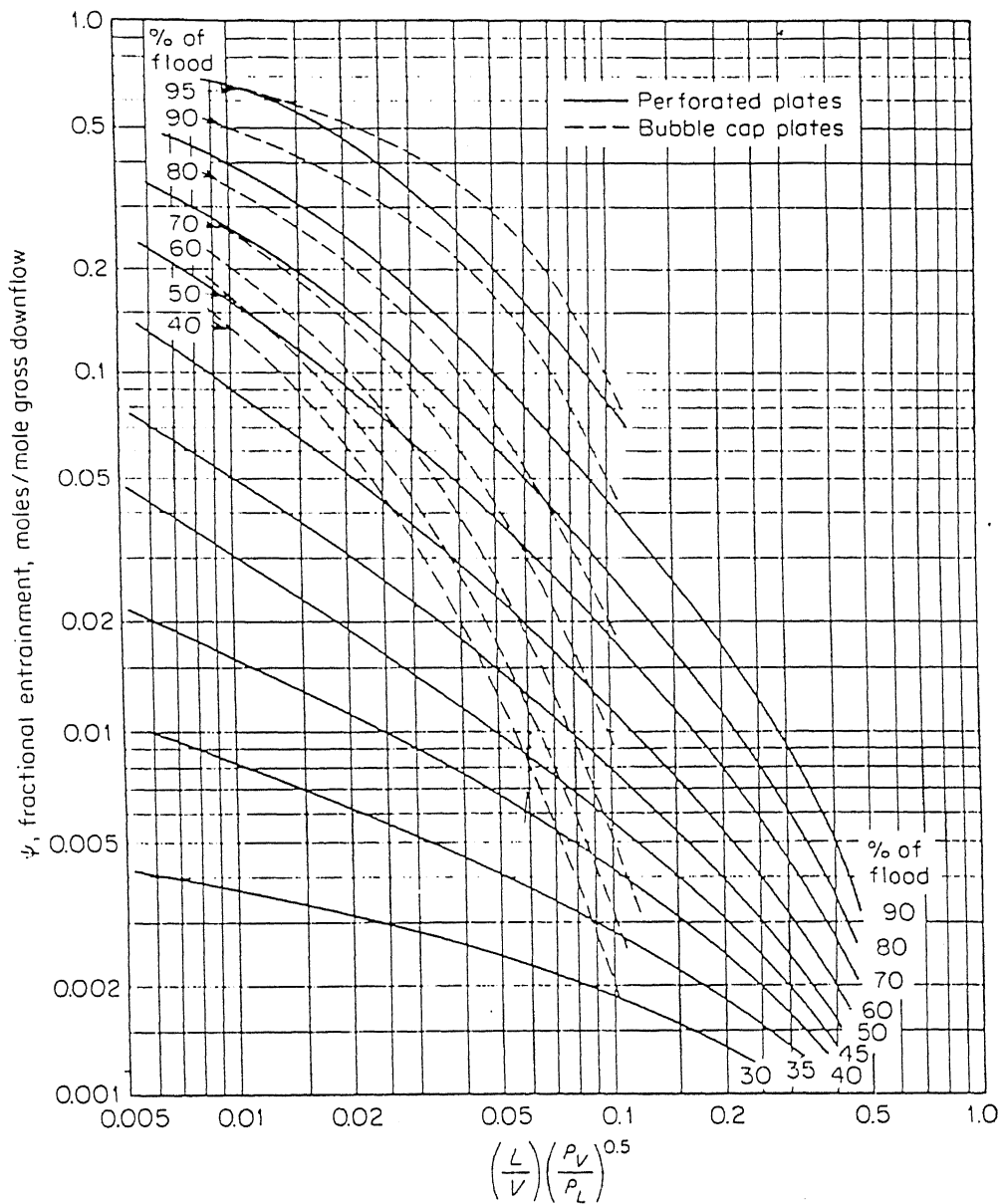


Figure 2.9 Entrainment Correlation
(Source : Winkle, 1967)

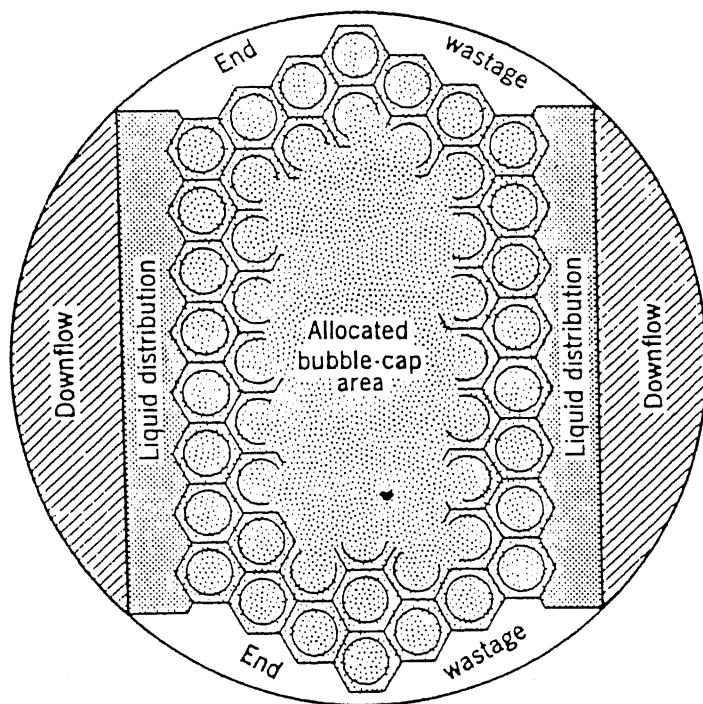


Figure 2.10 Classification of Tray Area
(Source : Smith, 1963)

Tray spacing. Tray spacing varies with the column diameter.

The recommended values are given below:

Column dia (ft)	Tray spacing (in.)
<2.5	12
2.5 - 4.0	18
4.0 - 24.0	24
>24.0	36

Cap pitch and spacing. Triangular cap pitch is recommended because this gives the maximum number of bubble caps per unit tray area for any given cap spacing. The practical range of cap spacing is between 1. and 3 in., measured between outside diameters of adjacent caps. Usually, it is taken as 25% of the cap diameter.

Size of bubble caps. As a rough guide for the selection of cap diameter, it is recommended that the cap size be chosen on the basis of column size as follows:

Column dia, ft	Cap dia, in.
<5.0	3
5.0 - 16.0	4
>16.0	6

The number of different bubble-cap designs which have been employed is almost endless. In order to simplify tray design and increase interchangeability, a set of standard bubble caps has been proposed. These are presented in Table 2.10.

Skirt clearance. The recommended range of skirt clearance is from 0.5 to 1.5 in. The selection of skirt clearance within this range involves determining the optimum balance of tray dynamic factors.

TABLE 2.10 Standard Bubble-cap Designs

Material	Carbon steel			Alloy steel		
Nominal size, in.	3	4	6	3	4	6
Cap:						
U.S. Standard gauge	12	12	12	16	16	16
OD, in.	3.093	4.093	6.093	2.999	3.999	5.999
ID, in.	2.875	3.875	5.875	2.875	3.875	5.875
Height over-all, in.	2.500	3.000	3.750	2.500	3.000	3.750
Number of slots	20	26	39	20	26	39
Types of slots	Trpzl.	Trpzl.	Trpzl.	Trpzl.	Trpzl.	Trpzl.
Slot width, in.:						
Bottom	0.333	0.333	0.333	0.333	0.333	0.333
Top	0.167	0.167	0.167	0.167	0.167	0.167
Slot height, in.	1.000	1.250	1.500	1.000	1.250	1.500
Height shroud ring, in.	0.250	0.250	0.250	0.250	0.250	0.250
Riser:						
U.S. Standard gauge	12	12	12	16	16	16
OD, in.	2.093	2.718	4.093	1.999	2.624	3.999
ID, in.	1.875	2.500	3.875	1.875	2.500	3.875
Standard heights, in.:						
0.5-in. skirt height	2.250	2.500	2.750	2.250	2.500	2.750
1.0-in. skirt height	2.750	3.000	3.250	2.750	3.000	3.250
1.5-in. skirt height	3.250	3.500	3.750	3.250	3.500	3.750
Riser-slot seal, in.	0.500	0.500	0.500	0.500	0.500	0.500
Cap areas, in. ² :						
Riser†	2.65	4.80	11.68	2.65	4.80	11.68
Reversal	3.99	7.30	17.40	4.18	7.55	17.80
Annular	3.05	5.99	13.95	3.35	6.38	14.55
Slot	5.00	8.12	14.64	5.00	8.12	14.64
Cap	7.50	13.15	29.0	7.07	12.60	28.3
Area ratios:						
Reversal/riser	1.50	1.52	1.49	1.58	1.57	1.52
Annular/riser	1.15	1.25	1.20	1.26	1.33	1.25
Slot/riser	1.89	1.69	1.25	1.89	1.69	1.25
Slot/cap	0.67	0.62	0.50	0.71	0.65	0.52

| Not generally recommended because of lower efficiency.
 | The trapezoidal shape is frequently modified by rounding at top and bottom to facilitate die stamping.
 ‡ Allowing for 3/8-in. hold-down bolt.

(Source: Smith, 1963).

Slot seal. Some slot seal is necessary to force the vapour to bubble through and contact the liquid. Since the actual slot seal is dependent on the liquid height over the weir and liquid gradient as well as the static seal, the seal should be selected on the basis of the dynamic slot seal. For proper operation of the plate column, the value of the dynamic slot seal shall be in the range of 1.0-2.0 in.

Evaluation of pressure drop and liquid backup in downcomers

In a column there are flow-energy losses in both vapour and liquid flow regions. In terms of column operation these losses are evidenced as pressure drop through the plate and through the column and as liquid backup in the downcomers which may become great enough to cause flooding. The symbols to be used in the various equations utilized for bubble-cap and perforated-plate pressure-drop calculations are defined as shown in Figure 2.11.

The pressure drop and the liquid backup in bubble-cap plate columns can be evaluated by

$$\Delta H_T = h_{rc} + h_{so} + \beta h_{ds} \quad (2.13)$$

and

$$H_d = \Delta H_T + h_w + h_{ow} + \Delta + h_d \quad (2.14)$$

where

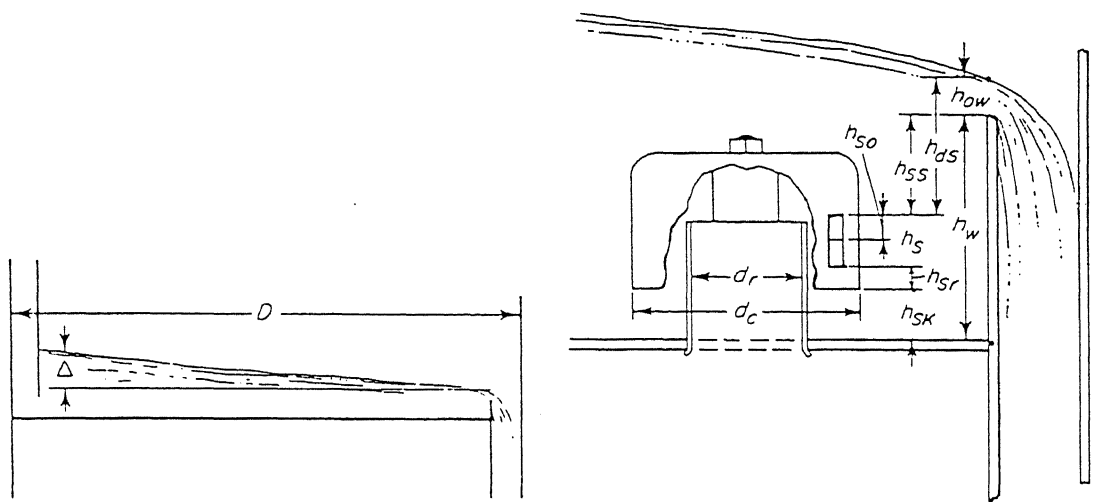
ΔH_T = pressure drop, in. liquid

H_d = liquid backup in the downcomer, in. liquid

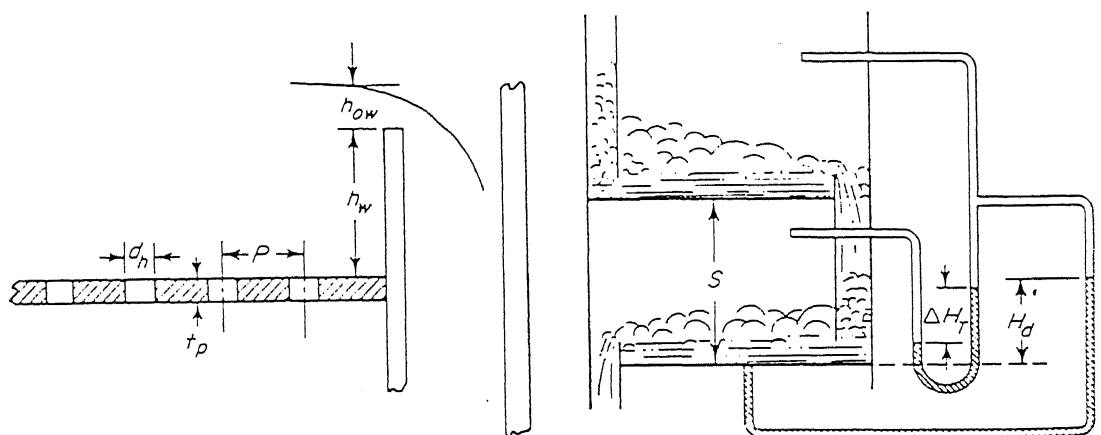
h_w = weir height, in.

h_{ow} = height of crest over weir, in.

Δ = corrected liquid gradient across plate, in. liquid



bubble-cap plate.



perforated plate.

Figure 2.11 Definition of Symbols
(Source : Winkle, 1967)

h_d = equivalent head loss through downcomer assembly, in.
liquid

h_{rc} = equivalent headloss through wet cap, in. liquid

h_{so} = slot opening measured from top of slot, in.

h_{ds} = dynamic seal, in.

β = aeration factor.

The terms in Eqs. (2.13) and (2.14) are defined and evaluated quantitatively by the following definitions and recommended equations:

h_w is the weir height in inches measured from the surface on the tray to the top of the weir (Figure 2.11). This is a design variable only.

h_{ow} designates the height of the liquid crest over the weir (Figure 2.11) in inches of the fluid flowing. It is defined as

$$h_{ow} = 0.48 F_w \left(\frac{Q_L}{l_w} \right)^{0.67} \quad (2.15)$$

F_w is read from Figure 2.12 for segmental weirs; for circular weirs $F_w = 1.0$. Q_L is the liquid flow rate in gpm and l_w is the weir length in inches.

h_d represents the liquid head in inches of fluid system equivalent to the pressure drop caused by the liquid flow in the downcomer. It is defined as

$$h_d = 0.03 \left[\frac{Q_L}{100 A_{dm}} \right]^2 \quad (2.16)$$

where

Q_L = liquid flow rate, gpm

A_{dm} = minimum area through which liquid flows in the
downcomer assembly, sq.ft

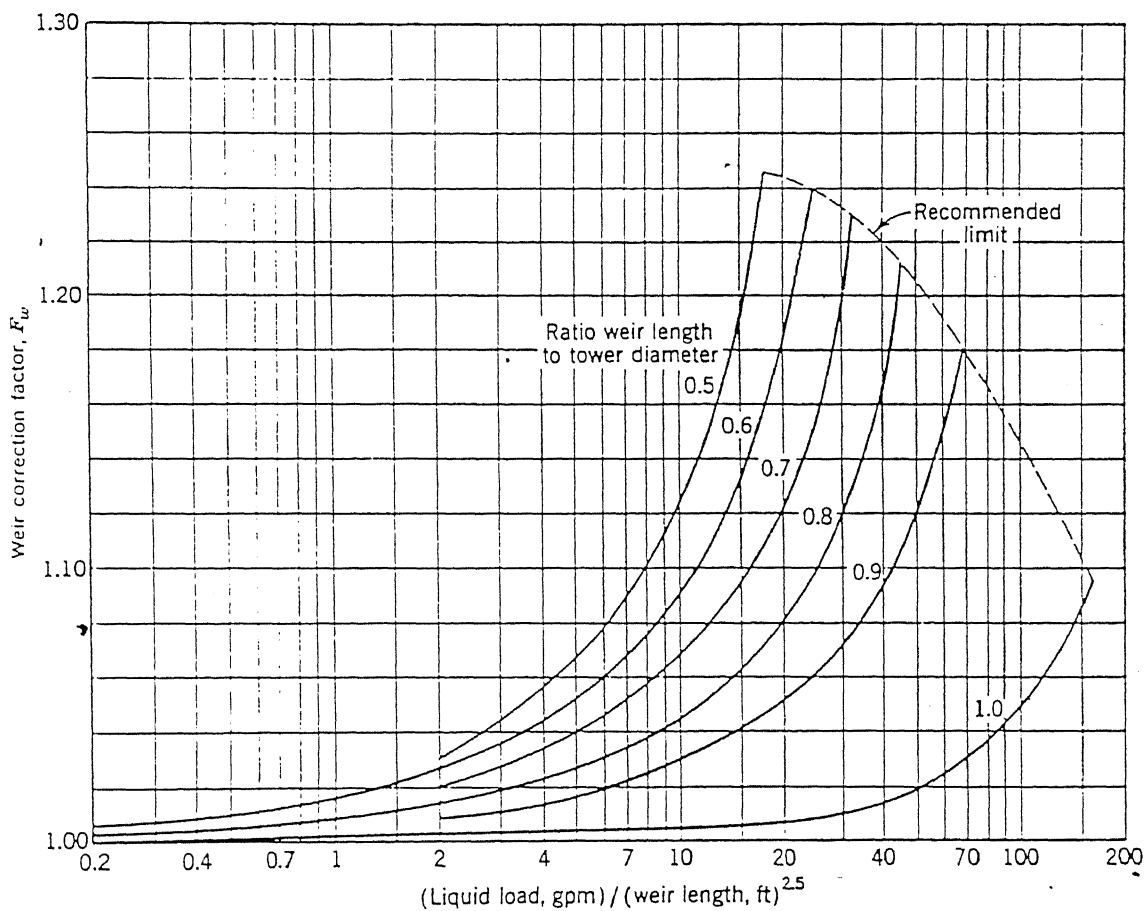


Figure 2.12 Correlation of F_w , Weir Formula Correction Factor, for Constricting Column Wall
(Source : Smith, 1963)

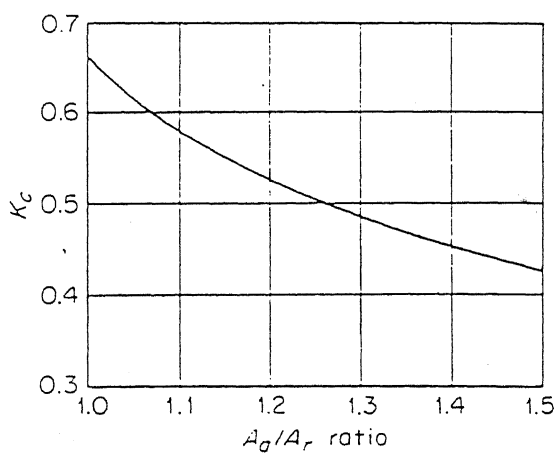


Figure 2.13 Bubble-cap Pressure Drop Constant
(Source : Winkle, 1967)

h_{rc} corresponds to the headloss in inches of fluid system caused by the vapour flow through the wet cap assembly. It is defined as

$$h_{rc} = K_c \frac{\rho_v}{\rho_L} \left(\frac{Q_v}{A_r} \right)^2 \quad (2.17)$$

where

Q_v = tray vapour load, cu.ft/sec

A_r = total riser area per tray, sq.ft

K_c is obtained from Figure 2.13.

h_{so} can be read directly as percent of slot height for various shaped slots as a function of vapour load from Figure 2.14. A_s is the total slot area per plate in sq.ft. h_{so} shall not be more than 100 percent of slot height.

h_{ds} represents the liquid headloss in inches of fluid caused by resistance to vapour flow through the liquid and froth above the slots. It is defined as

$$h_{ds} = h_{ss} + h_{ow} + \frac{\Delta}{2} \quad (2.18)$$

The aeration factor, β is obtained from Figure 2.15.

Δ is the difference in the height of the liquid crest flowing over the weir and the height of the liquid on the inlet side of the tray — both measured from the same reference elevation, usually the tray surface. The value of Δ' , uncorrected liquid gradient per row of caps is obtained from Figure 2.16. The correction of liquid gradient for vapour load is made through use of Figure 2.17. Thus the corrected gradient is calculated by

$$\Delta = C_v \Delta' \quad (2.19)$$

The mean tray width is given by

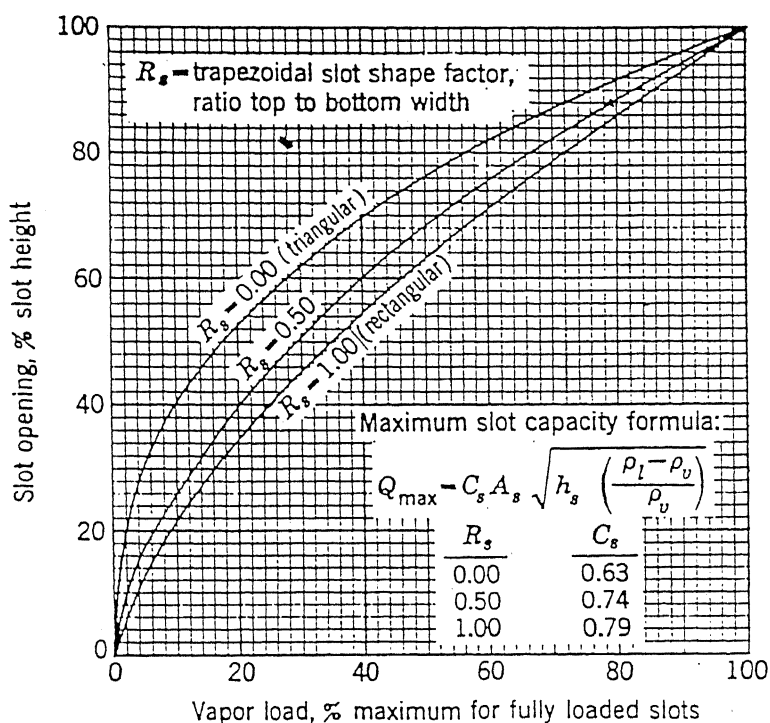


Figure 2.14 Generalized Correlation for Slot Opening
(Source : Smith, 1963)

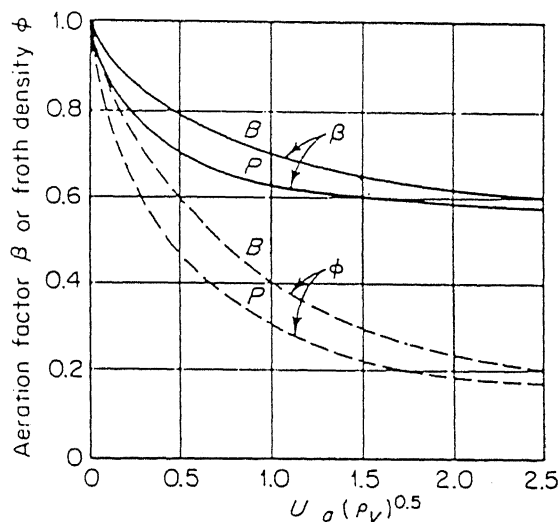


Figure 2.15 Aeration Factor and Froth Density
B-Bubble-cap Plates, P-Perforated Plates
(Source : Winkle, 1967)

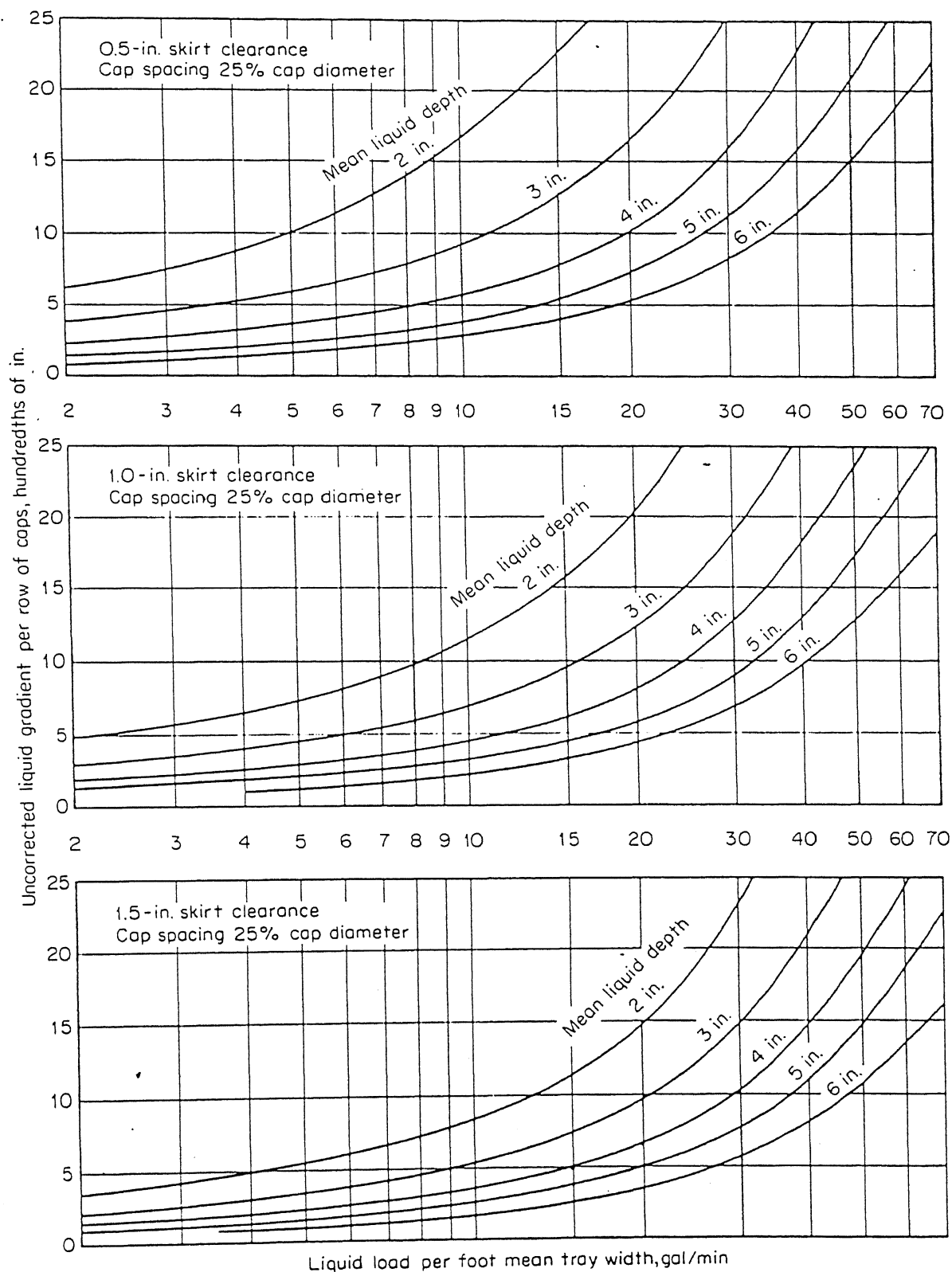


Figure 2.16 Liquid Gradient Chart- for Equilateral Triangular Cap Pitch
(Source : Winkle, 1967)

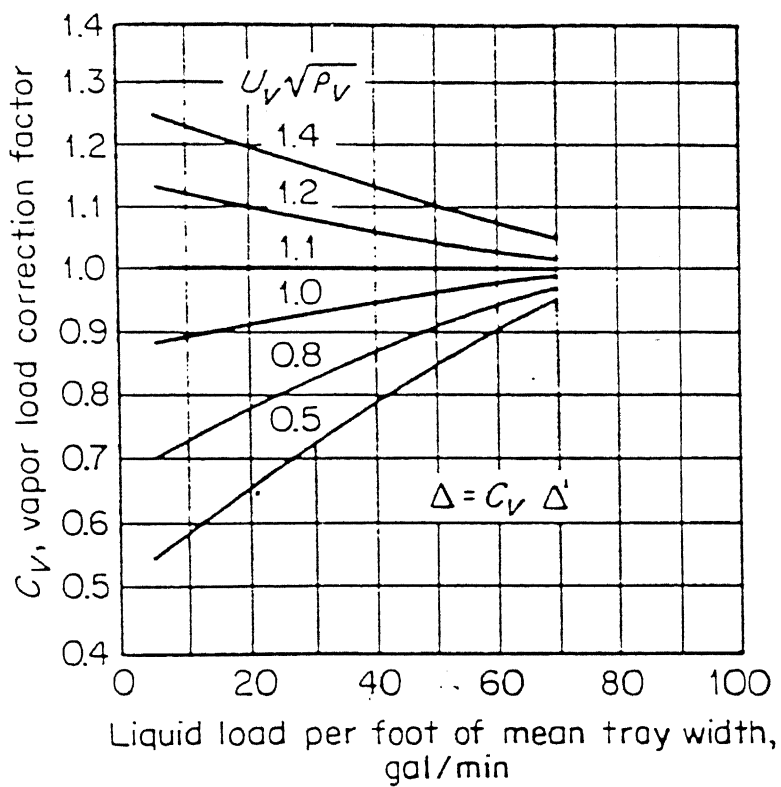


Figure 2.17 Correction of Liquid Gradient for Gas Load
(Source : Winkle, 1967)

$$W_a = \frac{D + l_w}{2} \quad (2.20)$$

where

W_a = total flow width across tray normal to flow, ft

D = column diameter, ft

l_w = weir length, ft.

Downcomer residence time

A certain residence time of liquid in the downcomer is necessary in order to allow collapse of foam. If the residence time is too short, vapour may be carried down to the next tray and danger of choking arises. The true residence time of aerated mass in the downcomer is

$$\text{Residence time, sec.} = \frac{A_d H_d}{12 Q'_L} \quad (2.21)$$

where

A_d = downcomer area, sq.ft

H_d = liquid backup in the downcomer, in

Q'_L = liquid flow rate, ft³/sec.

It is recommended that the residence time shall not be less than 5 sec.

2.4.3 Tray Hydraulics: Perforated Trays

Liquid entrainment

Liquid entrainment can be predicted from Figure 2.9. If the entrainment is less than 0.10 then the tray performance is good else the tray spacing has to be increased.

Design standards

Area terms. A number of different area designations are used in the design of sieve trays. These areas and their recommended

ranges are summarized here.

- i) Column area, A_t is the total internal cross-sectional area of the tower.
- ii) Downcomer area, A_d is the cross-sectional area at the top of the downcomer(s). For a segmental downcomer, it is the area of the segment formed by the overflow weir and the tower wall. The downcomer area is usually between 8 to 12 percent of the column area.
- iii) Net area, A_n is the area for gas flow above the tray. In the common single crossflow tray, $A_n = A_t - A_d$.
- iv) Active area, A_a is the general area where aeration occurs. For most design cases, A_a is taken as the total area between inlet and outlet weirs, and when straight segmental downcomers are used with single crossflow, $A_a = A_t - 2A_d$.
- v) Hole area, A_h is the total area open to gas flow. The hole area is usually between 6 to 12 percent of the column area.
- vi) Open area refers to the ratio of hole area to total area and can be calculated from the following equations:

Equilateral triangular pitch:

$$\text{Open area} = 0.905 \left(\frac{\text{hole diameter}}{\text{pitch}} \right)^2 \quad (2.22)$$

Square pitch:

$$\text{Open area} = 0.785 \left(\frac{\text{hole diameter}}{\text{pitch}} \right)^2 \quad (2.23)$$

Hole diameter and spacing. Hole diameters of 1/8 to 1/2 in. are commonly employed in sieve tray designs. Small hole size contributes to good gas dispersion, low pressure drop, low

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weeping, and low entrainment. Large holes are less easily fouled. The hole spacing is usually between 2.5 to 3.0 times the hole diameter.

Tray spacing. As a rough guide for the selection of tray spacing, it is recommended that the tray spacing be chosen on the basis of column size as follows:

Column dia, ft	Tray spacing, in
4 or less	18
4 - 10	24
10 - 24	30
24 or more	36

Plate thickness. The recommended values of plate thickness is given below:

Hole dia, in.	Plate thickness/hole diameter	
	Stainless steel	Carbon steel
1/8	0.65	
3/16	0.43	
1/4	0.32	
3/8	0.22	0.5
1/2	0.16	0.38
5/8	0.17	0.3
3/4	0.11	0.25

Evaluation of pressure drop and liquid backup in downcomers

The pressure drop and the liquid backup in perforated plate columns can be evaluated by

$$\Delta H_T = h_o + \beta(h_w + h_{ow} + \frac{\Delta}{2}) + h_\sigma \quad (2.24)$$

and

$$H_d = \Delta H_T + h_w + h_{ow} + \Delta + h_d \quad (2.25)$$

where

ΔH_T = pressure drop, in. liquid

H_d = liquid backup in the downcomer, in. liquid

h_w = weir height, in.

h_{ow} = height of crest over weir, in.

Δ = liquid gradient across plate, in. liquid

h_d = equivalent headloss through downcomer assembly, in. liquid

h_o = equivalent dry-plate pressure drop through holes, in. liquid

h_σ = equivalent surface-tension headloss, in. liquid

β = aeration factor.

The symbols to be used in the various equations utilized for perforated plate pressure drop calculations are defined as shown in Figure 2.11. h_{ow} and h_d can be determined from Eqs. (2.15) and (2.16) respectively, whereas h_w is a design variable. β is determined from Figure 2.15.

The term h_o represents the equivalent dry-plate pressure drop in inches of liquid system caused by gas passage through the holes. It is defined as

$$h_o = 0.186 \left(\frac{U_h}{C_{vo}} \right)^2 \frac{\rho_V}{\rho_L} \quad (2.26)$$

where

U_h = gas velocity through holes, ft/sec

C_{vo} = discharge coefficient (determined from Figure 2.18)

The term h_{σ} represents the headloss required to overcome surface tension effect in forming froth and foam and forcing the gas through the aerated mass. It is defined as

$$h_{\sigma} = \frac{0.04 \sigma}{\rho_L d_h} \quad (2.27)$$

where

σ = the surface tension of the liquid at the temperature of the plate, dynes/cm

d_h = hole diameter, in.

For perforated plates the hydraulic gradient Δ may be calculated by

$$\Delta \text{ (in. liquid)} = \frac{12 f U_f^2 Z_L}{g R_h} \quad (2.28)$$

where

f = friction factor

U_f = velocity of froth, ft/sec

Z_L = distance between weirs, ft

g = acceleration of gravity, 32.2 ft/sec²

R_h = hydraulic radius of the aerated mass, ft.

The foam friction factor, f is correlated in Figure 2.19 with the Reynolds modulus by

$$Re_h = \frac{R_h U_f \rho_L}{\mu_L} \quad (2.29)$$

The hydraulic radius of the aerated liquid is defined by

$$R_h = \frac{h_f W_a}{2h_f + 12W_a} \quad (2.30)$$

where

W_a = total flow width across tray normal to flow, ft

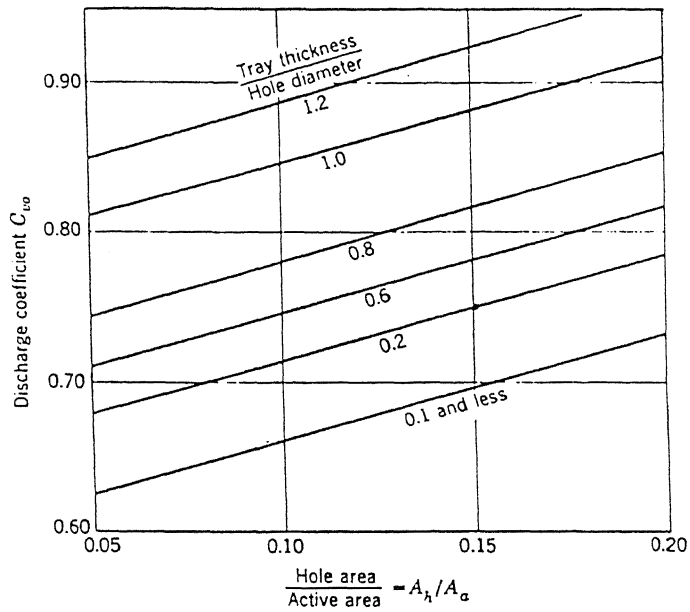


Figure 2.18 Discharge Coefficient for Gas Flow, sieve trays
(Source : Smith, 1963)

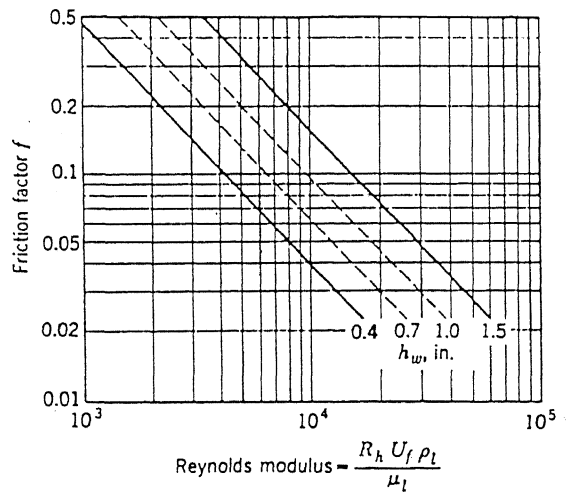


Figure 2.19 Friction Factor for Froth Crossflow, sieve trays
(Source : Smith, 1963)

h_f = height of froth on tray, in.

U_f is the velocity of froth which is the same as the velocity of the clear liquid calculated by

$$U_f = \frac{12Q'_L}{h_c W_a} \quad (2.31)$$

where

Q'_L = liquid flow rate, ft^3/sec

h_c = clear liquid height on tray, in.

also

$$h_f = \frac{h_c}{2\beta - 1} \quad (2.32)$$

Downcomer residence time

The residence time of aerated mass in the downcomer is obtained from Eq. (2.21). It shall not be less than 3 sec.

Weeping

Just as entrainment represents an upper limit to tray operation, excessive flow of liquid through the perforations represents a lower limit. At steady state, liquid will not drain through the perforations as long as surface tension effects and vapour-pressure drop through the perforations are present to prevent it. Figure 2.20 shows a correlation for checking weeping. It may be postulated that

$$h_h + h_\sigma \geq h_c \quad (2.33)$$

is a sufficient condition to prevent drainage. Here, h_h is the pressure drop due to vapour flow through the perforations and h_σ is the head of liquid necessary to overcome surface tension of liquid over the perforations.

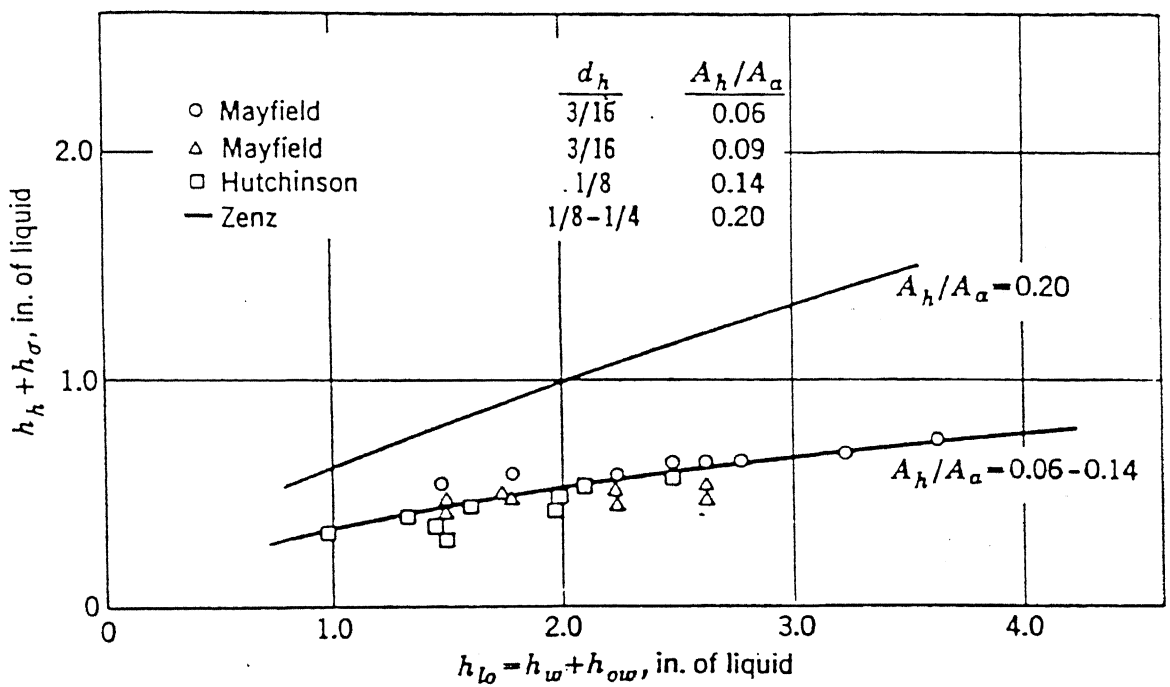


Figure 2.20 Weeping, sieve trays
(Source : Smith, 1963)

2.4.4 Tray Efficiency

The efficiency of a tray for mass transfer depends upon three sets of design parameters:

1. The system — composition and properties.
2. Flow conditions — rates of through-put.
3. Geometry — plate type and dimensions.

The designer has little control over the first set, but he can deal effectively with the other two. His ultimate concern is with overall column efficiency, E_{oc} .

The best established theoretical method for predicting E_{oc} is that of the A.I.Ch.E. in bubble tray design manual (Chilton and Perry, 1983). It is based on the sequential prediction of point efficiency, Murphree efficiency, and overall column efficiency

$$E_{og} \longrightarrow E_{mv} \longrightarrow E_{oc}$$

The point efficiency, E_{og} can be expressed as

$$E_{og} = 1 - \exp(-N_{og}) \quad (2.34)$$

where

$$N_{og} = \frac{1}{1/N_g + \lambda/N_l} \quad (2.35)$$

where

- N_g = gas-phase transfer units
- N_l = liquid-phase transfer units
- λ = mG_m/L_m (stripping factor)
- m = slope of equilibrium curve
- G_m = gas rate, moles/sec
- L_m = liquid rate, moles/sec.

Gas-phase transfer units, N_g , is given by

$$N_g = \frac{0.776 + 0.116 h_w - 0.290 U_a p_G^{0.5} + 0.0217 (Q_L/W_a)}{Sc_g^{0.5}} \quad (2.36)$$

where

h_w = weir height, in.

U_a = gas velocity through active area, ft/sec

Q_L = liquid flow rate, gpm

W_a = total flow width across tray normal to flow, ft

Sc_g = gas-phase Schmidt number, $\mu_G/\rho_G D_G$.

Liquid-phase transfer units, N_l is given by

$$N_l = (1.065 \times 10^4 D_L)^{0.5} (0.26 U_a p_G^{0.5} + 0.15) \left(\frac{h_c A_a}{12 Q'_L} \right) \quad (2.37)$$

where

$$h_c = \beta (h_w + h_{ow}) \quad (2.38)$$

Here Q'_L is the liquid flow rate in ft^3/sec and A_a is the active area of the plate in ft^2 .

The murphree efficiency, E_{mv} can be expressed as

$$E_{mv} = \frac{1}{\lambda} [\exp(\lambda E_{og}) - 1] \quad (2.39)$$

Calculated values of E_{mv} must be corrected for entrainment, if any, by

$$\frac{E_a}{E_{mv}} = \frac{1}{1 + E_{mv} [\psi / (1 - \psi)]} \quad (2.40)$$

where

E_a = corrected efficiency

ψ = fractional entrainment (Figure 2.9).

The resulting corrected efficiency E_a is then converted to column efficiency by

$$E_{oc} = \frac{\log[1 + E_a(\lambda - 1)]}{\log \lambda} \quad (2.41)$$

2.5 INCINERATION

2.5.1 General

Incineration is a controlled oxidation process used for destruction of vaporous volatile organic compound (VOC) or some toxic gaseous emissions from industrial waste gases. In the process, the VOC content of waste gases reacts at high temperatures with oxygen to form carbon dioxide and water, while liberating heat. Three parameters: temperature, residence time (also referred to as retention time or dwell time) and turbulence (the "three T_s ") have an interrelated effect upon the final combustion performance. They are not independent variables since changing one affects the other two.

The rate at which a combustible compound is oxidized is greatly affected by temperature. The higher the temperature, the faster the oxidation reaction will proceed. To maintain combustion of a waste, the amount of energy released by the combusted waste must be sufficient to heat the incoming waste (and air) up to its ignition temperature; otherwise, a fuel must be added. Most incinerators operate at higher temperature than the ignition temperature, which is a minimum temperature.

Time and temperature affect incineration in much the same manner as temperature and pressure affect the volume of a gas. When one variable is increased, the other may be decreased with the same end result. With a higher temperature, a shorter residence

time can achieve the same degree of oxidation. The reverse is also true; a higher residence time allows the use of a lower temperature. The choice between higher temperature or longer residence time is based on economic considerations. Increasing residence time involves using a larger incineration chamber, resulting in a higher capital cost. Raising the operating temperature increases fuel usage, which also adds to the operating cost. Fuel costs are the major operating expense for most incinerators.

Proper mixing is important in incineration processes for two reasons. First, for complete combustion to occur, every particle of waste and fuel must come in contact with air (oxygen). If this does not happen, unreacted waste and fuel will be exhausted from the stack. Second, not all of the fuel or waste stream is able to be in direct contact with the burner flame.

Oxygen is necessary for incineration to occur. To achieve complete incineration of a compound, a sufficient supply of oxygen must be present to convert all of the carbon to carbon dioxide. If an insufficient amount of oxygen is supplied, the mixture is referred to as rich. There is not enough oxygen to combine with all the fuel and waste so that incomplete incineration occurs. If more amount of oxygen is supplied, the mixture is referred to as lean. The added oxygen plays no part in the oxidation reaction and passes through the incinerator. Oxygen for the incineration process is supplied by using air.

2.5.2 Description of Equipment

Equipment used to control waste gases by incineration can be divided into three categories, viz., direct incineration or

flaring, thermal oxidation, and catalytic oxidation. Catalytic oxidation is generally not recommended for industrial waste gases because of high initial cost, operational troubles, and less flexibility in operation. Only flaring and thermal oxidation have been incorporated in the present work.

2.5.3 Thermal Incinerators

The thermal incinerator is a refractory lined vessel fitted with a nozzle-burner maintained by a combination of auxiliary fuel, waste gas compounds and supplemental air added when necessary. Upon passing through the flame, the waste gas is heated from its inlet temperature to the required reactor temperature. In general, the design of a thermal incinerator consists of:

1. Determining the amount of auxiliary fuel required.
2. Determining the amount of oxygen (or ambient air) required.
3. Determining the physical dimensions of the incinerator.

Though, estimations of auxiliary fuel requirement and flue gas flow rate are the primary parameters established in the incinerator design, one other parameter that must be established is the pressure drop across the incinerator system. The estimation of actual pressure drop requirements involves complex calculations based on the specific system's waste gas and flue gas conditions and equipment used, and is beyond the scope of the present work. For the purposes of preliminary estimates, however, an approximate value of 4 inches H_2O can be used (Vaart et.al., 1991).

A residence time of 0.2 to 2.0 sec is recommended for thermal incinerators (Air Pollution Engineering Manual, 1992). A length-to-diameter ratio of 2.0 to 3.0 is usually employed. The average gas velocity can range from as low as 10 fps to as high as 50 fps.

High velocities are required to prevent settling of particulates (if present) and to minimize the dangers of flashback and fire hazards.

Based on the composition of the waste gas stream, Katari et.al. (1987) have categorized the waste gases into six categories. Figure 2.21 provides a flow chart for categorizing a waste gas to determine its suitability for incineration and establish its auxiliary fuel and oxygen requirements. The auxiliary fuel and oxygen requirements of waste gas categories are also presented in Table 2.11.

Once waste gas characteristics and temperatures at various stages of the incineration process are identified, energy and material balances around the incinerator system establish the flue gas flow rate leaving the system and the amount of auxiliary fuel required. Actual energy and material balances around the incinerator system to derive these equations are given in the literature (Katari et.al., 1987). Equations for estimating fuel requirements are presented in Table 2.12.

The different terms used in Table 2.12 are:

Q_2 = Waste gas flow rate, scfm

Q_3 = Auxiliary fuel flow rate, scfm

Cp_5 = Mean heat capacity for the temperature interval of ΔT_5 ,
Btu/ft³ °F

Cp_2 = Mean heat capacity for the temperature interval of ΔT_2 ,
Btu/ft³ °F

ΔT_5 = Temperature interval from T_R (70°F) to T_5 (Flue gas temperature), °F

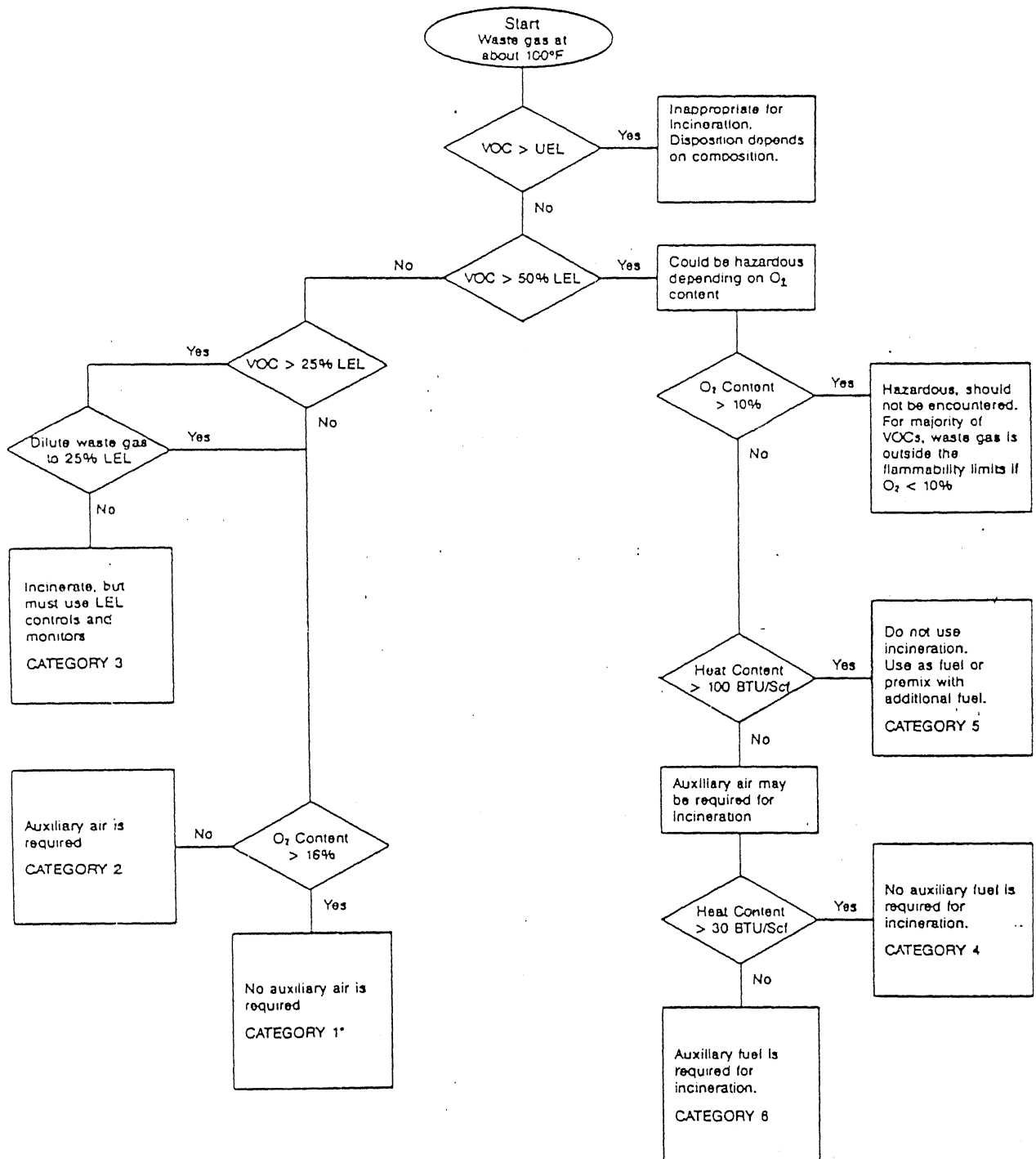


Figure 2.21 Flow Chart for Categorization of a Waste Gas
(Source : Katari et al., 1987)

TABLE 2.11 Categorization of Waste Gas Streams

Waste-gas		
Category	Composition	Auxiliaries and other requirements
1.	Mixture of VOC, air, and inert gas with $>16\%$ O_2 and a VOC content $<25\%$ LEL (i.e., heat content <13 Btu/ft ³)	Auxiliary fuel is required. No auxiliary air is required.
2.	Mixture of VOC, air, and inert gas with $>16\%$ O_2 and a VOC content between 25 and 50% LEL (i.e., heat content between 13 to 26 Btu/ft ³)	Dilution air is required to lower the heat content to <13 Btu/ft ³ . (Alternative to dilution air is installation of LEL monitors.)
3	Mixture of VOC, air, and inert gas with $<16\%$ O_2	Treat this waste stream the same as categories 1 and 2, except augment the portions of the waste gas used for fuel burning with outside air to bring its O_2 content to above 16 percent.
4	Mixture of VOC and inert gas with zero to negligible amount of O_2 (air) and <100 Btu/scf heat content	Oxidize it directly with a sufficient amount of air.
5	Mixture of VOC and inert gas with zero to negligible amount of O_2 (air) and >100 Btu/scf heat	Premix and use it as a fuel.
6	Mixture of VOC and inert gas with zero to negligible amount of O_2 and heat content insufficient to raise the waste gas to the combustion temperature	Auxiliary fuel and combustion air for both the waste gas VOC and fuel are required.

(Source: Katari et.al., 1987).

TABLE 2.12 Equations for Estimating Fuel Requirements

Waste gas category	General equation for fuel, ft^3/ft^3 of waste gas
1	$\frac{Q_3}{Q_2} = \frac{1.1 \text{ Cp}_5 \Delta T_5 - \text{Cp}_2 \Delta T_2 - h_2}{h_3 - 1.1 \text{ Cp}_5 \Delta T_5}$
2	$\frac{Q_3}{Q_2} = \frac{1.1 \text{ Cp}_5 \Delta T_5 - \text{Cp}_2 \Delta T_2 - h_2}{h_3 - 1.1 \text{ Cp}_5 \Delta T_5}$
3	$\frac{Q_3}{Q_2} = \frac{1.1 \text{ Cp}_5 \Delta T_5 - \text{Cp}_2 \Delta T_2 - h_2}{(h_3 - 1.1 \text{ Cp}_5 \Delta T_5) - 10.54 \text{ Cp}_5 \Delta T_5 (1 + E) / (1 + K)}$
4	$\frac{Q_3}{Q_2} = \frac{1.1 \text{ Cp}_5 \Delta T_5 + 1.1 [\sum m_i (X+Y/4-Z/2)_i] 4.79 (1+E) \text{ Cp}_5 \Delta T_5 - \text{Cp}_2 \Delta T_2 - h_2}{h_3}$
5	Waste gas is premixed and used as fuel. -
6	$\frac{Q_3}{Q_2} = \frac{1.1 [1 + [\sum m_i (X+Y/4-Z/2)_i - m_{O_2}] 4.79] \text{ Cp}_5 \Delta T_5 - (\text{Cp}_2 \Delta T_2 + h_2)}{(h_3 - 1.1 \text{ Cp}_5 \Delta T_5) - 10.54 (1+E) \text{ Cp}_5 \Delta T_5 / (1+K)}$

(Source: Katari et.al., 1987).

ΔT_2 = Temperature interval from T_R (70°F) to T_2 (waste gas temperature), $^\circ\text{F}$

T_R = Reference temperature (70°F)

h_2 = Waste gas heat content (Btu/ft^3)

h_3 = Lower heating value of fuel, Btu/ft^3

E = Excess air used

K = Constant = $9.58E / [(h_3/\text{Cp}_5) - 1]$

m_i = Volume content of i th VOC component in the waste gas

X, Y, Z = Atoms of C, H_2 , and O_2 in the VOC

m_{O_2} = Volume content of oxygen in the waste gas.

The value of C_p and K are established based on the waste gas temperature, flue gas combustion temperature, and the type of fuel used. The overall C_p value of the flue gas is calculated more accurately from the C_p values of the flue gas components, which include CO_2 , H_2O , O_2 , and N_2 . Alternatively, as a fair approximation, the C_p value of air can be substituted for C_p values of the flue gas and the waste gas.

2.5.4 Flare

In flaring, volatile organic compounds (VOC) are piped to a remote, usually elevated, location and burned in an open flame in the open air using a specially designed burner tip, auxiliary fuel, and steam or air to promote mixing for nearly complete VOC destruction. Completeness of combustion in a flare is governed by flame temperature, residence time in the combustion zone, turbulent mixing of the components to complete the oxidation reaction, and available oxygen for free radical formation. Combustion is complete if all VOCs are converted to carbon dioxide and water. Incomplete combustion results in some of the VOC being unaltered or converted to other organic compounds such as aldehydes or acids.

Flares can be used to control almost any VOC stream, and can handle fluctuations in VOC concentration, flow rate, heating value, and inerts content. Flaring is appropriate for continuous, batch and variable flow vent stream applications. The majority of chemical plants and refineries have existing flare systems designed to relieve emergency process upsets that require release of large volumes of gas.

Design Procedures

Flare design is influenced by several factors, including the availability of space, the characteristics of the flare gas (namely composition, quantity, and pressure level) and occupational concerns. The sizing of flares requires determination of the required flare tip diameter and height.

Auxiliary fuel requirement. The amount of auxiliary fuel required is calculated based on maintaining the vent gas stream net heating value at the minimum of 300 Btu/scf (Evans et.al., 1992):

$$Q_2 h_2 + Q_3 h_3 = (Q_2 + Q_3) (300 \text{ Btu/scf}) \quad (2.42)$$

where

Q_2 = waste gas flow rate, scfm

Q_3 = auxiliary fuel flow rate, scfm

h_2 = waste gas heating value, Btu/scf

h_3 = auxiliary fuel heating value, Btu/scf.

Rearranging gives:

$$\frac{Q_3}{Q_2} = \frac{300 - h_2}{h_3 - 300} \quad (2.43)$$

Flare tip diameter. Flare tip diameter is generally sized on a velocity basis, although pressure drop must also be checked. The maximum velocity of a steam-assisted, elevated flare is determined as follows (Evans et.al., 1992):

Net heating value of
vent stream, B_v (Btu/scf)

Maximum velocity
 V_{\max} (ft/sec)

300

60

300 - 1000

$$\log(V_{\max}) = (B_v + 1214) / 852$$

>1000

400

By determining the maximum allowed velocity and knowing the total volumetric flow rate, including waste gas and auxiliary fuel, a minimum flare tip diameter can be calculated. It is standard practice to size the flare so that the design velocity is 80 percent of V_{\max} .

A pressure drop calculation is required at this point to ensure that the vent stream has sufficient pressure to overcome the pressure drop occurring through the flare system at maximum flow conditions. The pressure drop calculation is site specific but must take into account losses through the collection header and piping, the knock-out drum, the liquid seal, the flare stack, the gas seal and finally the flare tip (Evans et.al., 1992). Calculation of the pressure drop, however, is beyond the scope of the present work. Typical total system pressure drop ranges from about 10 to 25 psi (Evans et.al., 1992).

Flare height. The required flare stack height is given by the expression (Evans et.al., 1992)

$$H^2 = \frac{\tau f_h R}{4 \cdot \pi K} \quad (2.44)$$

where

H = flare height, ft

τ = fraction of heat intensity transmitted

f_h = fraction of heat radiated

R = net heat release (Btu/hr)

K = allowable radiation (500 Btu/hr-ft²).

The conservative design approach used here ignores wind effects. For estimating purposes, however, assume all of the heat

radiated is transmitted (i.e., $\tau = 1$). In general, the fraction of heat radiated increases as the stack diameter increases. If stream-specific data are not available, a design basis of $f_h = 0.2$ will give conservative results (Evans et.al., 1992). The heat release, R , is calculated by multiplying flare gas flow rate (ft^3/min) by the net heating value (Btu/ft^3).

Purge gas and steam requirements. Purge gas, typically natural gas, N_2 , or CO_2 , is used to maintain a minimum required positive flow through the system so as to prevent low flow flashback problems and to avoid flame instability. To ensure a positive flow through all flare components, purge gas injection should be at the farthest upstream point in the flare transport piping. Using the conservative gas velocity value of 0.04 ft/sec (Evans et.al., 1992) and knowing the flare diameter, the purge gas requirement can be calculated. For general consideration, the quantity of steam required can be assumed to be 0.4 pounds of steam per pound of flare gas (Evans et.al., 1992). Operating a flare at too high a steam-to-gas ratio is not only costly, but also results in a lower combustion efficiency and a noise nuisance.

Knock-out drum. The knock-out drum is used to remove any liquids that may be in the vent stream. Flares designed to control continuous vent streams generally have vertical knock-out drums, whereas emergency flares typically have horizontal vessels.

Liquid particles will separate when the residence time of the vapour is greater than the time required to travel the available vertical height at the dropout velocity of the liquid particles, i.e., the velocity is less than the dropout velocity. In addition,

the vertical gas velocity must be sufficiently low to permit the liquid droplets to fall. The dropout velocity, U , of a particle in a stream, or the maximum design gas velocity, is calculated by (Evans et.al., 1992)

$$U \text{ (ft/sec)} = G_f \sqrt{\frac{\rho_L - \rho_V}{\rho_V}} \quad (2.45)$$

The design gas velocity factor, G_f , ranges from 0.15 to 0.25 for vertical gravity separators at 85 percent of flooding (Evans et.al., 1992). An average value of 0.20 is generally used. Once the maximum design gas velocity has been determined the minimum vessel cross-sectional area can be determined by knowing the vent stream flow rate.

The vessel thickness is determined based on the following values (Evans et.al., 1992):

<u>Vessel diameter, ft.</u>	<u>Vessel thickness, in.</u>
<3	0.25
3 - 6	0.375
6 - 9	0.5
9 - 12	0.75
>12	1.0

The vessel height is, usually, taken as three times the vessel diameter (Evans et.al., 1992).

2.6 ADSORPTION

Adsorption is a process wherein molecules of a fluid or gas contact and adhere to the surface of a solid. This phenomenon is believed to occur generally in nature, regardless of the particular solids and gases involved. The forces present in this

intermolecular activity have been identified as being of two major types: Van der Waals forces and chemical or ionic forces. The bonding force playing the major role in the adsorption process identifies either physical adsorption, in which the Van der Waals molecular interaction force predominates, or chemisorption, where chemical reaction forces provide the predominant intermolecular bonds. Both physical adsorption and chemical adsorption are exothermic reactions and both liberate heat during the adsorption phase.

The amount of gas adsorbed by a solid depends on the natures of the adsorbent and gas being adsorbed, the surface area of the adsorbent, the temperature, and the pressure of the gas.

Four important adsorbents widely used industrially are activated carbon, activated alumina, silica gel, and molecular sieves. The first three of these are amorphous adsorbents with a non-uniform internal structure. Molecular sieves, however, are crystalline and have, therefore, an internal structure of regularly spaced cavities with interconnecting pores of definite size. Details of the properties peculiar to the various materials are best obtained directly from the manufacturer.

Fixed-bed adsorbers are the usual choice for the control of gaseous pollutants when adsorption is the desired method of control. Design calculations include the determination of type, number and size of adsorbers, and are related to pressure drop and mass transfer. Design is, however, not only based on theory but also on industrial experience.

Adsorption is used in the case of a very lean mixture of the gaseous pollutants in the carrier gas. Adsorption, therefore, is not favoured for industrial gaseous pollutants control where the concentration of pollutants is relatively high and the volume of the waste gas to be handled is large. Design of adsorption equipment is not incorporated in the present work. Design fundamentals are, however, available in the literature (Brauer and Varma, 1981; Buonicore and Theodore, 1982).

2.7 CONDENSATION

Condensation is the process of converting a gas to liquid. Any gas can be reduced to a liquid by sufficiently lowering its temperature and/or increasing its pressure. The most common approach is to reduce the temperature of the gas stream, since increasing the pressure of a gas can be expensive.

When a hot gas stream contacts a cooler medium, heat is transferred from the hot gases to the cooler medium. As the temperature of the gas stream is decreased, the average kinetic energy of the gas is reduced. Ultimately, the gas molecules are slowed down and crowded so closely together that the attractive forces (Van der Waals forces) between the molecules cause them to condense to a liquid. The actual conditions at which a particular gas molecule will condense depends on its physical and chemical properties.

Condensers differ in the means of removing heat and the type of device used. The two different means of condensing are direct contact, where the cooling medium and the condensate are intimately mixed and combined, and indirect (or surface), where the cooling

medium and vapour/condensate are separated by a surface area of some type.

Contact condensers are simpler, less expensive to install, and require less auxiliary equipment and maintenance. The coolant from a contact condenser often cannot be reused and may pose a waste disposal problem unless the dilution of the pollutant is sufficient to meet regulatory requirements.

Surface condensers form the bulk of the condensers used for gaseous pollutants control. Among the applicable types of surface condensers are shell and tube, double pipe, spiral plate, flat plate, air-cooled, and various extended-surface tubular units.

Condenser, more often than not, is a secondary control device since it cannot achieve the collection efficiency required by industry using ordinarily available and economical cooling medium. Condensers are typically used as pretreatment devices. They can be used ahead of other gaseous pollutants control equipment to reduce the total gas volume to be treated by more expensive control equipment.

Design of condensers is not incorporated in the present work. Detailed design fundamentals are, however, available in the literature (Perry, 1950; Buonicore and Theodore, 1982; Air Pollution Engineering Manual, 1992).

2.8 SELECTION OF AN EQUIPMENT

The final selection of an equipment is usually dictated by that equipment capable of achieving compliance with regulatory codes at the lowest annual cost, which includes installation, operation and maintenance costs. However, in order to select an

equipment on economic basis, knowledge of the particular application and site is essential. It is pertinent to point out here that the present work is not an attempt to calculate optimal design of a unit in terms of cost-effectiveness.

A preliminary selection, however, may be performed based on the particular application and by reviewing the advantages and disadvantages of each type of gaseous pollutants control equipment. There are many situations in which knowledge of the capabilities of the various control options, combined with common sense, will simplify the selection procedure. The selection of a particular equipment for a particular application has been left to the user of the package.

3. PACKAGE PROGRAM STRUCTURE

3.1 GENERAL PROGRAM LOGIC

The present package has been developed keeping in mind the end user to be an environmental engineer. It is also assumed that the user may have little or no programming knowledge. Thus the package has been written such that the user does not have to call upon special programming skills or knowledge, except for knowing elementary concepts about operation of a terminal and giving execution commands. The standard PASCAL has been used keeping in view the portability of the software.

The package has a main program which reads in the global inputs, viz, the code number, the process to be employed, waste gas flow rate, and waste gas temperature. Once the process to be employed has been chosen by the user, the control is transferred to the appropriate procedure.

The procedure, then, asks the user to provide certain process specific inputs and then to choose the equipment to be designed. Specific inputs on the type of the equipment are asked for and the package comes up with a design which closely meets these requirements. A simplified and abridged algorithm of the package is presented hereunder.

A Simplified and Abridged Algorithm of Main Program

Input: Choice of process for operation

```
{  
1.  write (enter code no.)          (* on user screen *)  
2.  read (code no.)  
3.  If (code no. = O.K.) then continue else to to 1  
4.  DATAINPUT (global data)  
5.  PROCESS  
6.  write (if the user wants to continue)  
                                     (* on user screen *)  
7.  read (choice)  
8.  if (choice = yes) then go to 4.  
}
```

```
procedure: DATAINPUT (global data)
```

```
input:    Qv, T, n, y(i)
```

```
{
read (Qv)      (* Qv is the waste gas flow rate *)
read (T)        (* T is the waste gas temperature *)
read (n)        (* n is the number of components present
                  in the waste gas stream *)
for i = 1 to n do
  {
    read (y(i))  (* y(i) is the volume content of ith
                  component in the waste gas *)
  }
}
```

```
procedure: PROCESS
```

```
input:  choice of process
```

```
{
read (user's choice of process (1) - Absorption
                                     (2) - Incineration)

if (choice = 1) then
  ABSORPTION
else if (choice = 2) then
  INCINERATION
}
```



```
procedure:  ABSORPTION
```

```
input :  process specific inputs, equipment specific inputs
output:  equipment design parameters, pressure-drop
```

```
{
read (process specific inputs)
COMPUTE - LIQUID-REQUIREMENT
COMPUTE - OUTLET-LIQUID-COMPOSITION
write (solute concentrations at inlet and outlet conditions)
                                         (* to file AB_E *)
write (liquid-requirement)              (* to file AB_E *)
write ('Equilibrium data written to file AB_E')
                                         (* on user screen *)

read (user's choice of equipment (1) - Packed Column
                                         (2) - Plate Column)

if (choice = 1) then
    PACKED-COLUMN
else if (choice = 2) then
    PLATE-COLUMN
{
procedure:  PACKED-COLUMN
read (equipment specific inputs)
COMPUTE - EQUIPMENT-DIMENSIONS
COMPUTE - PRESSURE-DROP
write (design-parameters)                (* to file PC_D *)
write (pressure-drop)                   (* to file PC_D *)
write ('Design of packed column written to file PC_D')
                                         (* on user screen *)
}
{
procedure:  PLATE-COLUMN
```


3.2 EQUIPMENT SELECTION AND ITS STRUCTURES

Design of the following equipment have been implemented in the present version of the software:

- 1) Packed Column (Absorption)
- 2) Bubble Cap Plate Column (Absorption)
- 3) Perforated Plate Column (Absorption)
- 4) Flare (Incineration)
- 5) Thermal Incinerator (Incineration).

The user has the option to choose and design any of the equipment listed above. Certain specific inputs have to be provided depending on the equipment chosen. The outputs are written in files and name of the file, in which the outputs is written, is flashed on the screen. If either no equipment is chosen or the desired action for the chosen equipment is complete, the control is transferred to the main program and the user now has an option to continue with further design or he can quit the system.

3.3 THE PROCEDURES

There are around 18 procedures in the package, which can be broadly classified as the following:

- (1) Procedures for data input and output.
- (2) Procedures for interpolating a two dimensional table.
- (3) Procedures for equilibrium calculations in case of absorption.
- (4) Procedures for calculation of design parameters of various equipment.
- (5) Procedures for finding pressure drop for certain equipment.

3.4 AUXILIARY FILES

The package has eight auxiliary files along with the main program which are taken as input to it. These auxiliary files are:

- (1) PC_PACK: This file contains values of the Packing Factor, F , for different sizes of various packings, to be used in the design of packed column.
- (2) PC_GASPH: This file contains values of the constants, for use in determining gas-phase height of a transfer unit, to be used in the design of packed column.
- (3) PC_LIQPH: This file contains values of the constants, for use in determining liquid-phase height of a transfer unit, to be used in the design of packed column.
- (4) DIF_GAS: This file contains a list of diffusion coefficients of gases in air, at 25°C and 1 atm., for reference.
- (5) DIF_LIQ: This file contains a list of diffusion coefficients of gases in liquid, at 20°C , for reference.
- (6) TRAY_SEL: This file contains a chart for tentative selection of tray type, viz., reverse flow, cross-flow, double pass, or cascade double pass, based on the estimated tower diameter and the range of liquid flow rate.
- (7) AREA_DIS: This file contains a chart for the distribution of total tray area into four different areas, viz., downflow area, liquid-distribution area, end-wastage, and allocated cap area (determined by difference), for different tray types and tower diameters.
- (8) BUB_DES: This file contains a chart for the standard design of bubble cap.

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In the files DIF_GAS and DIF_LIQ new values can be added without any change in the program structure, whereas, any change in the other files should be accompanied by a corresponding modification in the program structure.

4. PACKAGE OPERATION AND USER INTERACTION

4.1 GENERAL

The package can be compiled on any machine with a PASCAL or ayTurbo PASCAL compiler. The resulting executable file can be runydirectly in the presence of the auxiliary files listed in Sectiony3.4.

The package works in the British system of units because most of the design fundamentals available in the literature are in these units only. However, for the benefit of the users, all the input and output data are in the SI units so that the user has to deal with the SI units only and the machine will do the conversion of SI units to British system of units and vice-versa.

The package operation starts with asking the user to enter the code number. If the code number entered is wrong, a message for the same would be flashed on the screen and, the computer would again ask for the code number. The operation is repeated unless and until the code number entered is correct. The package then asks the user to select the process to be employed for the removal of gaseous pollutants. If one of the processes is selected, the control is transferred to the process chosen.

4.2 ABSORPTION

If the chosen process is absorption, the package asks for the following inputs:

1. temperature of the liquid, $^{\circ}\text{C}$;
2. operating pressure, N/m^2 ;
3. name of the liquid;

4. average molecular weight of the liquid;
5. liquid density, Kg/m^3 ;
6. liquid viscosity, Ns/m^2 ;
7. liquid surface tension, N/m ;
8. name of the carrier gas;
9. average molecular weight of the carrier gas;
10. carrier gas density, Kg/m^3 ;
11. carrier gas viscosity, Ns/m^2 ;
12. composition of inlet and outlet gas;
13. composition of inlet liquid;
14. diffusivity of the gas in the air and the liquid, m^2/s ;
15. equilibrium curve data expressed as mole fraction;
16. ratio of design to actual liquid flow rate (a default value of 1.3 has already been entered.)

The package, then, calculates the composition of the outlet liquid and the liquid flow rate required. The output is stored in a file AB_E.

The user is then asked to select the equipment to be designed. The options are packed column and plate column.

If packed column is chosen, the user is asked to select the type of packing and the size of packing. A default value of 60 percent has been entered in the package for the flood point at which the column is to operate, but the user has the option to change this value if he wants. The package then designs the packed column and calculates the pressure drop. The output is stored in a file PC_D.

If plate column is chosen, the user is asked to select the type of tray. The options are bubble-cap plate column and perforated plate column. The user is also asked to select the tray material, downcomer type and hole pattern (for perforated plates), and the flood point (a default value of 80 percent has already been entered). The package assumes the value of certain parameters, like tray spacing, hole size (for perforated plates) etc., and then calculates the column dimensions, including the number of actual plates required. The package also calculates the other tray parameters and a tray layout is developed. Then all the tray dynamic factors are calculated and checked for this layout, and the changes are made if required and the procedure is repeated. The package then calculates the pressure drop across the column. In evaluating the final tray parameters a multi-dimensional search is carried out to minimize the pressure drop. The design of bubble-cap plate column is stored in a file BPC_D and the design of perforated plate column is stored in a file PPC_D.

4.3 INCINERATION

If the chosen process is incineration of waste gas, the package asks for the waste gas heat content. The waste gas flow rate, for determining heat content, is measured at the standard conditions of 25°C and 1 atmosphere. The user is then asked to select the equipment to be designed. The options are flare and thermal incinerator.

If thermal incinerator is chosen, the package asks for the following additional inputs:

1. combustion temperature;

2. number of combustible component in the waste gas;
3. volume content of each of the combustible component present;
4. upper and lower explosive limits of each of the combustible component present;
5. atoms of carbon, hydrogen, and oxygen in each of the combustible component present;
6. volume content of oxygen in the carrier gas (a default value of 20.86 percent, for air, has already been entered);
7. mean heat capacity of the waste gas (or carrier gas) at the waste gas temperature and at the combustion temperature;
8. fuel heat content (if fuel is required).

The package, then, calculates the auxiliary fuel requirement, the ambient air requirement, and the incinerator dimensions. The output is stored in a file TH_D.

If flare is chosen, the package asks for the following additional inputs:

1. waste gas density, Kg/m^3 ;
2. fuel heat content, J/m^3 (if fuel is required). The flow rate of fuel is measured at the standard conditions of 25°C and 1y atm. ;
3. fraction of heat intensity transmitted (a default value of 1.0 has already been entered);
4. fraction of heat radiated (a default value of 0.2 has already been entered);
5. moisture density, Kg/m^3 (if moisture is present in the waste gas).

The package, then, calculates the auxiliary fuel requirement, flare dimensions, knockout drum dimensions (if moisture is present in the waste gas), and purge gas requirement. If the designed flare diameter and/or the flare height is very large, and is not commercially available, the user has a choice to go for the design of more than one flare. The output is stored in a file FL_D.

The results of typical runs for the above are given in the Appendix 1. A comparison of the package output with the design problems from literature is shown in the Appendix 2.

5. SUMMARY

In the present work, a software package has been developed for design of various equipment for the control of gaseous air pollutants present in the effluent gas stream.

The package has been written in PASCAL and, compiled and tested on HP 9000/S 800 superminis. The package is interactive in the sense that all the inputs have to be given at the respective prompts showing the units in which the same must be entered. Though the package employs British system of units, for the benefit of the user, the SI units are to be used for the inputs and the outputs are also in the SI units. The outputs generated are stored in files for easy reference later.

The outputs produced by the package for some sample runs have been given in the Appendix 1. The working of the package has been checked stage by stage for all the units by using design examples from various references. Comparison of the results of the package output and those from the literature are given in the Appendix 2.

The package can be used to design various equipment employing absorption and incineration for the control of gaseous pollutants. It is hoped that this package will serve as an effective tool in the hands of an environmental engineer/consultant and that his innovative skills will find this package useful for numerous other purposes than those listed in this thesis.

Cost analysis has not been included in the present work, therefore, the present work is not an effort towards the optimal design of a control equipment. The selection of a particular equipment for a particular application has been left to the user of the package.

6. LIMITATIONS OF THE PRESENT WORK AND SUGGESTIONS FOR FUTURE WORK

In light of the certain limitations of the present work there is a lot of scope for improvement of this package to enhance its usefulness and versatility. Some of them may be listed as under:

1. Efforts may be made to include cost analysis for the equipment to be designed so that the final selection of an equipment may be made on the basis of cost-effectiveness.
2. The design of other equipment, used for gaseous pollutants control, such as adsorber, condenser, valve tray column, catalytic incinerator, venturi scrubber etc., may be implemented in the present package.
3. Efforts may be made towards design of various control equipment in series or in parallel to achieve specific requirement.
4. In the present package, a specified set of input data has to be given in a specified order. The package may be made more interactive and user-friendly so that the user has the option to design a particular equipment for any given set of condition as input data.
5. Lastly, the present work may be taken to be a part of development of an exhaustive package in the area of air pollution control engineering. A software package for design of particulate control equipment (Sinha, 1995) and another for

design of local exhaust ventilation system (Anand, 1996) have already been developed. Thus, an effort may be made to integrate these packages to make a comprehensive air pollution control package.

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APPENDIX 1 : TYPICAL OUTPUTS FOR DESIGN OF EQUIPMENT

PROCESS: ABSORPTION

EQUILIBRIUM CALCULATIONS

Total gas flow rate = $10.0 \text{ m}^3/\text{s}$

Temperature of the liquid:

At the top of the column = 25°C

At the bottom of the column = 30°C

Operating pressure (at the top of the column) = 101330 N/m^2

Scrubbing Liquid: WATER

Density of the scrubbing liquid = 1000 Kg/m^3

Carrier Gas: AIR

Density of the carrier gas = 1.183 Kg/m^3

Number of gaseous pollutants present in the waste gas stream = 1

S.No. of the pollutant present = 1

Name: AMMONIA

Mole fraction of the pollutant in the inlet gas stream = 0.08

Percentage removal desired = 95

Mole fraction of the pollutant in the inlet liquid = 0.00001

Liquid flow rate required = $7.85441 \times 10^{-3} \text{ m}^3/\text{s}$

Mole fraction of ammonia in the outlet liquid = 0.06590

GAS ABSORPTION EQUIPMENT : PACKED COLUMN

Waste gas flow rate = $10.0 \text{ m}^3/\text{s}$

Liquid flow rate = $7.85441 \times 10^{-3} \text{ m}^3/\text{s}$

Operation: Countercurrent continuous operation

Packing Type : Raschig Rings - Ceramic

Packing size: 2 in.

Temperature of the liquid:

At the top of the column = 25°C

At the bottom of the column = 30°C

Operating Pressure:

At the top of the column = 101330 N/m^2

At the bottom of the column = 104540 N/m^2

Area of the column at the top = 5.424 m^2

Area of the column at the bottom = 5.779 m^2

Design area of the column = 5.779 m^2

Diameter of the column = 2.72 m

Number of transfer units = 6.75

Height of a transfer unit = 1.031 m

Overall height of the column = 6.959 m

Overall pressure drop = 2918.37 N/m^2

GAS ABSORPTION EQUIPMENT : PERFORATED PLATE COLUMN

Waste gas flow rate = $10.0 \text{ m}^3/\text{s}$

Liquid flow rate = $7.85441 \times 10^{-3} \text{ m}^3/\text{s}$

Temperature of the Liquid:

At the top of the column = 25°C

At the bottom of the column = 30°C

Operating Pressure :

At the top of the column = 101330 N/m^2

At the bottom of the column = 113534 N/m^2

Area of the column = 4.514 m^2

Diameter of the column = 2.40 m

Number of trays = 13

Tray spacing = 0.6 m

Tray Type : Perforated

Tray Material : Carbon Steel

Tray thickness = 4.5 mm

Tray Flow Pattern : Single-pass Crossflow

Downcomer Type : Straight, Segmental

Active area = 3.431 m^2

Hole area = 0.451 m^2

Downflow area = 0.542 m^2

Hole diameter = 9.0 mm

Hole Pattern : Equilateral Triangular Pitch

Hole spacing = 27.0 mm

Weir length = 1.846 m

Weir height = 50.0 mm

Downcomer clearance = 40.0 mm

Pressure drop per plate = 853.45 N/m²

Overall pressure drop = 11094.84 N/m²

GAS ABSORPTION EQUIPMENT : BUBBLE-CAP PLATE COLUMN

Waste gas flow rate = $10.0 \text{ m}^3/\text{s}$

Liquid flow rate = $7.85441 \times 10^{-3} \text{ m}^3/\text{s}$

Temperature of the Liquid:

At the top of the column = 25°C

At the bottom of the column = 30°C

Operating Pressure:

At the top of the column = 101330 N/m^2

At the bottom of the column = 113460 N/m^2

Area of the column = 4.002 m^2

Diameter of the column = 2.26 m

Number of trays = 14

Tray spacing = 0.6 m

Tray Type : Bubble-Cap

Bubble-cap Material : Alloy Steel

Tray Flow Pattern : Single-pass Crossflow

Downflow area = 0.400 m^2

Area under apron = 0.125 m^2

Weir length = 1.640 m

Weir height = 8.89 cm

Distance between weirs = 1.551 m

Cap diameter = 10.16 cm

Overall height of the cap = 7.62 cm

Number of caps per plate = 248

Number of rows of caps per plate = 20

Cap Pattern : Equilateral Triangular

Cap spacing = 2.54 cm

Type of Slots : Trapezoidal

Number of slots per cap = 26

Bottom width of slot = 0.85 cm

Top width of slot = 0.42 cm .

Height of slot = 3.17 cm

Height of shroud ring = 0.63 cm

Riser O.D. = 6.66 cm

Riser I.D. = 6.35 cm

Riser height = 7.62 cm

Skirt clearance = 2.54 cm

Cap area/cap = 81.29 cm^2

Slot area/cap = 52.39 cm^2

Riser area/cap = 30.97 cm^2

Annular area/cap = 41.16 cm^2

Pressure drop per plate = 787.68 N/m^2

Overall pressure drop = 11027.55 N/m^2

PROCESS : INCINERATION

UNIT : FLARE

Waste gas flow rate = $10 \text{ m}^3/\text{s}$

Waste gas heat content = 9000 kJ/m^3 (at 25°C , 1 atm)

Waste gas temperature = 35°C

Fuel : Natural Gas

Fuel heat content = 37236 kJ/m^3 (at 25°C , 1 atm)

Number of flares = 6

Flare diameter = 39.62 cm

Flare height = 13.702 metre

Fuel requirement for each flare = $0.1388 \text{ m}^3/\text{s}$

Number of vertical knock-out drums = 1

Diameter of knock-out drum = 2.762 metre

Height of knock-out drum = 8.287 metre

Thickness of knock-out drum = 1.90 cm

Purge-gas requirement for each flare = $1.50455 \times 10^{-3} \text{ m}^3/\text{s}$

UNIT : THERMAL INCINERATOR

Waste gas flow rate = $10 \text{ m}^3/\text{s}$

Waste gas temperature = 38°C

Combustion temperature = 870°C

Waste gas heat content = 335.0 kJ/m^3 (at 25°C , 1 atm)

Carrier Gas : AIR

Number of volatile organic compounds (VOCs)
present in the waste gas stream = 2

S.No. of the VOC present = 1

Name : Benzene

Fraction (by volume) present = 0.002

LEL for benzene = 0.014 ppmv

UEL for benzene = 0.071 ppmv

S.No. of the VOC present = 2

Name : Methyl Alcohol

Fraction (by volume) present = 0.002

LEL for methyl alcohol = 0.0672

UEL for methyl alcohol = 0.365

Fuel : Natural Gas

Fuel heat content = 33000 kJ/m^3 (at 25°C , 1 atm)

Ambient air requirement = Nil

Auxiliary fuel requirement = $0.0693 \text{ m}^3/\text{s}$

Volume of the incinerator = $10.0693 \text{ m}^3/\text{s}$

Diameter of the incinerator = 1.724 metre

Length of the incinerator = 4.311 metre

Residence time = 1.0 sec

APPENDIX 2 : COMPARISON OF PACKAGE OUTPUTS WITH DESIGN PROBLEMS FROM LITERATURE

DESIGN PROBLEM 1 : PACKED COLUMN

(Source: Wark and Warner, 1981, pp. 288-301)

Total gas flow rate = $0.2429 \text{ m}^3/\text{s}$

Temperature of the liquid (at bottom) = 20°C

Operating pressure (at bottom) = 101330 N/m^2

Composition:

Ammonia in the inlet gas stream = 8%

Air in the inlet gas stream = 92%

Removal of ammonia desired = 95%

Ammonia in the inlet liquid = 0

Packing Type : Raschig Rings - Ceramic

Packing Size : 1 in.

Flood point = 60 percent

Design to minimum liquid flow rate = 1.3

Scrubbing Liquid: Water

	From package	From literature
1. Liquid flow rate, m^3/s	1.95621×10^{-4}	1.96×10^{-4}
2. Mole fraction of ammonia in the outlet liquid	0.06596	0.066
3. Area of the column at the top, m^2	0.206	0.21
4. Area of the column at the bottom, m^2	0.22	0.223
5. Design area of the column, m^2	0.22	0.223
6. Diameter of the column, m	0.53	0.5334
7. Number of transfer unit	6.74	6.5
8. Height of a transfer unit, m	0.698	0.738
9. Overall height of the column, m	4.705	4.796
10. Overall pressure drop, N/m^2	2372.9	2491.74

DESIGN PROBLEM 2 : PERFORATED PLATE COLUMN

(Source: Smith, 1963, pp. 561-565)

Material : Essentially Benzene

Maximum gas load = 240000 lb/hr or 11.25 m³/s

Maximum liquid load = 200000 lb/hr or 577 gpm

Operating pressure = 101330 N/m²

Operating temperature = 80°C

Liquid density = 693.67 Kg/m³Gas density = 2.691 Kg/m³

Liquid surface tension = 0.021 N/m

	From Package	From Literature
1. Area of the column, m ²	9.129	8.83
2. Diameter of the column, m	3.41	3.36
3. Tray spacing, m	0.6	0.60
4. Tray material	Stainless steel	Stainless steel
5. Tray thickness, mm	1.95	1.98
6. Tray flow pattern	Double crossflow	Single crossflow
7. Downcomer type	Straight, segmental	Straight, segmental
8. Active area, m ²	6.938	6.711
9. Hole area, m ²	0.913	0.883
10. Downflow area, m ²	1.095	1.06
11. Hole diameter, mm	3.0	4.7
12. Weir height, mm	50.0	50.8
13. Downcomer clearance, mm	40.0	38.1
14. Pressure drop per plate, N/m ²	692.94	741.52

DESIGN PROBLEM 3 : BUBBLE-CAP PLATE COLUMN

(Source: Smith, 1963, pp. 527-534)

Material : Essentially Benzene

Maximum gas load = 240000 lb/hr or 11.25 m³/s

Maximum liquid load = 200000 lb/hr or 577 gpm

Operating pressure = 101330 N/m²

Operating temperature = 80°C

Liquid density = 693.67 Kg/m³Gas density = 2.691 Kg/m³

Liquid surface tension = 0.021 N/m

	From Package	From Literature
1. Area of the column, m ²	10.831	10.512
2. Diameter of the column, m	3.72	3.66
3. Tray spacing, m	0.6	0.6
4. Bubble-cap material	Carbon steel	Carbon steel
5. Tray flow pattern	Double crossflow	Double crossflow
6. Downflow area, m ²	2.166	2.026
7. Area under apron (side), m ²	0.142	0.185
8. Area under apron (centre), m ²	0.283	0.37
9. Weir length (side), m	1.857	1.829
10. Weir length (centre), m	3.714	3.659
11. Weir height, cm	8.89	7.62
12. Cap diameter, cm	10.16	10.16
13. Number of caps	532	560
14. Cap pattern	Equilateral triangular	Equilateral triangular
15. Cap spacing, cm	2.54	2.54
16. Skirt clearance , cm	2.54	2.54
17. Pressure drop per plate, N/m ²	598.47	622.23

DESIGN PROBLEM 4 : FLARE

(Source: Evans et.al., 1992)

Waste gas flow rate = $0.03 \text{ m}^3/\text{s}$ Waste gas heat content = 16719 kJ/m^3 (at 25°C , 1 atm)Waste gas temperature = 32.2°C System pressure = 68932 N/m^2 Moisture density = 794.6 Kg/m^3 Gas density = 1.353 Kg/m^3

	From Package	From Literature
1. Fuel requirement	Nil	Nil
2. Number of flares	1	1
3. Diameter of flare, cm	4.18	4.1656
4. Height of flare, m	2.506	2.5
5. Diameter of knock-out drum, m	0.161	0.16
6. Height of knock-out drum, m	0.483	0.48
7. Thickness of knock-out drum, cm	0.63	0.635
8. Purge gas requirement, m^3/s	1.67574×10^{-5}	-

DESIGN PROBLEM 5 : THERMAL INCINERATOR

(Source: Vaart, 1991)

Waste gas flow rate = $9.446 \text{ m}^3/\text{s}$ Waste gas temperature = 37.8°C Combustion temperature = 871.1°C

Composition:

Benzene (ppmv) = 1000

Methyl chloride (ppmv) = 1000

Air = Balance

Particulate content = Negligible

Moisture content = Negligible

Waste gas heat content = 155.65 kJ/m^3 (at 25°C , 1 atm)Fuel heat content = 32666.46 kJ/m^3 (at 25°C , 1 atm)

Residence time = 1 sec

	From Package	From Literature
1. Ambient air requirement, m^3/s	Nil	Nil
2. Auxiliary fuel requirement, m^3/s	0.0802	0.0789
3. Volume of the incinerator, m^3	9.5262	9.525
4. Diameter of the incinerator, m	1.693	1.7
5. Length of the incinerator, m	4.232	4.2